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INITIAL EARTHQUAKE CENTRIFUGE MODEL EXPERIMENTS FOR THE STUDY OF LIQUEFACTION

Final Technical Report

by

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SUMMARY

This project is a continuation of earlier research work by the Principal Investigator in support of the Earthquake Engineering Research Program, under the direction of the USAE Waterways Experiment Station at Vicksburg, Mississippi. The report describes the initial experiments in the program of studies planned under the EERP. These are intended to gather data suitable for the development of improved design approaches for the prediction of liquefaction under earthquake loading using the new centrifuge facility at the WES. A detailed experiment program has been developed for the first series of experiments studying the development of excess pore pressure in a level saturated sand bed under dynamic shaking at different effective overburden stresses. The initial experiments using the new large 'earthquake' shaker have been completed and data is presented and analysed.

LIST OF KEYWORDS

liquefaction
centrifuge
earthquake
model
experiment
sand

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1.0 INTRODUCTION

The use of the centrifuge for the study of earthquake related problems is now well established. One particular area of concern in the field which may be addressed by the analysis of centrifuge model experiment data is the prediction of liquefaction and its consequences. Design techniques for the prediction of liquefaction are generally accepted to be conservative, but in the absence of a substantial data-base of the actual behaviour of soils under correct initial stress conditions, there is little scope for improvement.

This research study is a continuation of earlier research in support of the Earthquake Engineering Research Program under the direction of the USAE Waterways Experiment Station, Vicksburg, Mississippi (Contract N68171-97-C-9012, Steedman (1997)). During this study, a detailed plan for the initial centrifuge model experiments was developed and the first experiments were conducted.

This report presents the experiment plan, and factual and interpretative reports describing the initial experiments using the WES centrifuge and the new earthquake actuator. The research has been documented throughout and a full suite of files is maintained at WES containing calculations, reports and data. Appendix A catalogues the list of computer files detailing the research.

2.0 EXPERIMENT PLAN

Liquefaction of soils under earthquake shaking is dependant on a range of factors, but design approaches commonly recognise two principal influences: the effect of the in-situ effective overburden pressure and the effect of the in-situ static shear stress. These two parameters are incorporated into calculations for the 'factor of safety against triggering' liquefaction by two factors, denoted Ka and Ks respectively. A full description of how these factors are used to compute the likelihood of liquefaction for any given deposit and earthquake time history following the approach of Seed and Harder (1990) was given by Steedman (1997) in the Final Technical Report under the preceding stage of this work.

The first stage in the experiment progam was to design a series of experiments to investigate Ka, the influence of effective overburden pressure. Under the large structures of interest to the USAE, the initial effective overburden pressures may be considerable, and therefore it was important to be able in the experiments to study a wide range of overburden pressures, from the 'standard' 1tsf against which design approaches are frequently normalised, upto 5 to 10 tsf, which may be representative of more typical conditions in the field.

The earthquake actuator on the recently commissioned centrifuge at WES provides a capability for such experiments. The Equivalent Shear Beam (ESB) model container was designed to provide a boundary condition in terms of lateral (shear) stiffness broadly comparable to conditions in the field

under the target overburden stresses and likely strains during earthquake loading. The design of the ESB container is analysed in more detail below.

The dimensions of the ESB container are 600mm deep by 800mm long and 315mm wide. At 50 gravities (g) this represents an equivalent prototype depth of 30m, length of 40m and width of around 16m.

In Appendix B, detailed calculations are presented for the design of an earthquake model using the WES ESB model container to provide a range of initial effective overburden pressures at the mid-depth of a loose layer 160mm deep (8m in the field). The first model, Model 1a, was based on parameters for Ottawa sand. Calculations for subsequent models were based on parameters for Nevada sand.

For the first models it was considered appropriate to base the loose layer on the bottom of the ESB container. As the overall depth required to provide 1 tsf at the centre of a loose layer (at 50g) is considerably less than the overall depth of the container, this decision was considered carefully. An alternative would have been to fill the ESB container and to have located the loose layer at the appropriate depth. This would have the advantage that the overall centre of gravity of the soil and ESB container would be similar in successive models potentially leading to a more repeatable dynamic response of the system. However, this would have then required a further dense layer beneath the loose layer which may have affected the drainage characteristics and base input motion, making comparison with models where the loose layer was located on the bottom of the box more difficult.

The total depth of sand in the ESB was calculated to be around 300mm. With the phreatic surface at ground level, and a relative density of around 57% in the upper layer, this will generate an effective vertical overburden pressure of 1 tsf (107 KPa) at mid-depth in a loose layer of around 35% relative density at 50g. Detailed calculations are presented in Appendix B, under Series 1 Model Design Summary. Calculations are presented both for Ottawa sand and for Nevada sand.

The instrumentation layout, shown in Figure 1 of the Earthquake Model Test Plan, Appendix B, was selected to provide duplication at critical locations, such as in the loose layer. In future model experiments, it is anticipated that additional pore pressure transducers would be available.

Following the 1 tsf model experiment, it is planned to carry out a 2 tsf experiment, and calculations relating to the design of this model are also attached in Appendix B. Designated Model 3 (as the base model would be constructed twice, using Ottawa sand and Nevada sand), the 160 mm deep sand layer would now be located beneath a deeper dense upper layer, around 370mm deep at a relative density of around 60%. Allowing for the thickness of base plates in the ESB container, this would mean that the 2 tsf model would essentially fill the full 600mm depth of the ESB at 50g.

To provide for higher levels of overburden a range of options have been considered. The first option is to lower the level of the phreatic surface in the upper dense layer, thus providing a higher effective overburden stress in the

underlying loose layer. Calculations (Appendix B, Series 1 Earthquake model design, Nevada sand) suggest that the maximum vertical effective overburden stress that can be achieved at mid-depth in a 160mm loose layer on the bottom of the ESB by this technique is slightly greater than 3 tsf (320 KPa).

To achieve higher effective overburden pressures in the loose layer will require either a higher g level or the use of a surcharge such as lead pellets. Calculations in Appendix B illustrate how a model providing 10 tsf at mid-depth in the loose layer can be achieved at 50g using a layer of lead pellets around 310mm deep overlying a dense sand layer 110mm deep, which itself overlies the loose sand layer. Such a depth of lead pellets may be impractical. It would certainly affect the dynamic characteristics of the ESB container. The alternative technique is simply to increase the g level, but for strict compatibility this would necessitate a change in the input driving frequency accordingly, which cannot at present be achieved until the hydraulic drive is installed.

For comparison, though, rough calculations show that with a suppressed phreatic surface a vertical effective overburden pressure of 5 tsf can be achieved at mid-depth in the target loose layer at a g level of around 74g (at which the equivalent prototype loose layer has been reduced to a model thickness of 108mm). Similarly, without the use of surcharges, a vertical effective overburden pressure of 10 tsf can be achieved at mid-depth in an 8m prototype equivalent loose layer at around 138g, within the design capacity of the earthquake actuator.

These options will require to be considered in more detail in future stages of this research program

3.0 MODEL 1a (1 tsf, Ottawa sand)

Model experiment 1a was carried out on 4 December 1997 at WES using the new earthquake actuator. This 1 tsf model was constructed using Ottawa sand; the actual as-built records of density, instrumentation etc are given in Appendix C, Earthquake Experiment Series Interpretative and Factual Reports. The Factual Report includes the time histories of all the instrumentation, showing the build-up of excess pore pressure in the loose and dense layers and the acceleration records from the accelerometers distrubuted throughout the model. A discussion of the experiment and interpretation of the data is given in the Model 1a Interpretative Report, which precedes the Factual Report in the Appendix.

The experiment confirmed that the earthquake actuator is well suited to the research program and that data can be captured which will meet the requirements of the proposed analyses, as described in the method outlined by Steedman (1997).

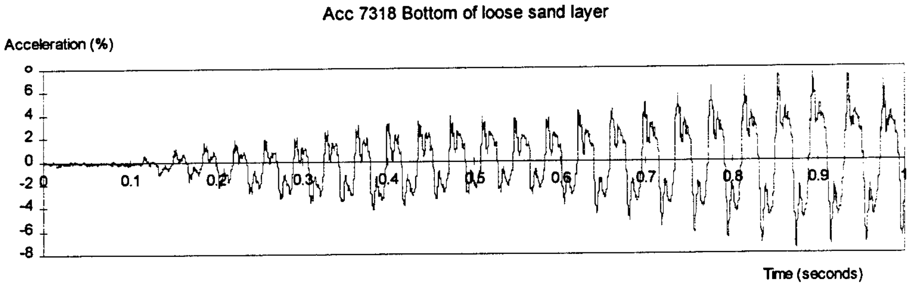


Figure 1

In Model 1a two earthquakes were triggered, with a moderate level of base input motion. In the first earthquake, Figure 1, the clutch mechanism was triggered twice, leading to a long duration event which peaked at a base input of around +/- 8%.

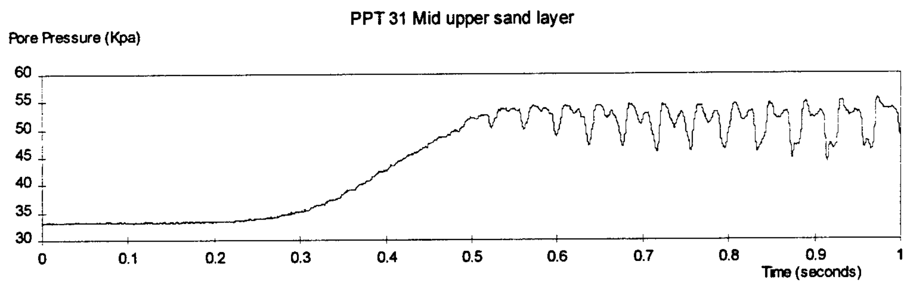


Figure 2

Motions in the model were amplified to a maximum of around +/- 10%, and extensive liquefaction and double frequency 'butterfly' cycling was observed in the upper sand layer, Figure 2.

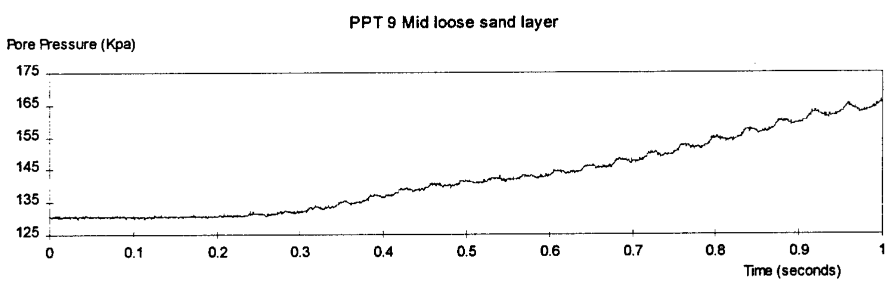


Figure 3

Excess pore pressures in the loose layer, Figure 3, reached around 30-40% by the end of the recording window. The final peak value is not known but it is not likely (based on the rate of increase with time) that full liquefaction in this layer was achieved.

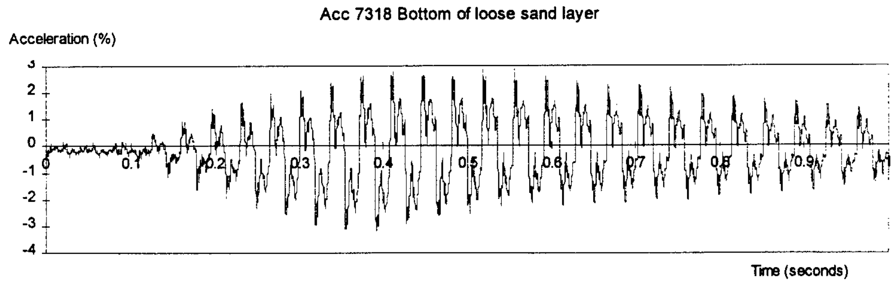


Figure 4

In the second earthquake, a base input motion with a peak value of around +/- 3% was generated over a duration of around 1 second (50 seconds equivalent in the field), Figure 4. Peak excess pore pressures in the loose layer reached only around 5-10% of the initial effective overburden stress, possibly due to densification after the first event and also due to the low level of input motion.

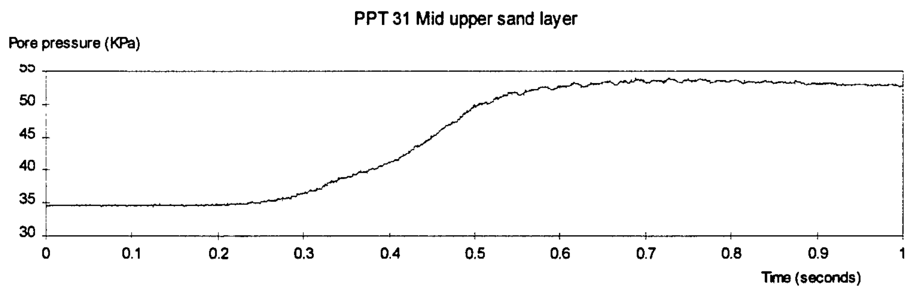


Figure 5

However PPT 31 in the middle of the upper (dense) sand layer showed liquefaction again within around 12 cycles of base shaking, Figure 5. In this event there was less 'double frequency' cycling after reaching full overburden than in the first earthquake, suggesting that there was a smaller degree of cyclic shear stress reaching this location. However, comparing the absolute magnitude of the value of excess pore pressure in earthquake 1 and 2, it is clear that they are very similar. To reach full liquefaction under such a relatively small amplitude of base shaking in a medium-dense sand is a significant result and will require further detailed analysis in subsequent stages of this research.

Spectral analysis of the input motion shows that the dominant driving frequency is around 27Hz (0.54 Hz prototype), a feature of the electric motor used to drive the system.

It is also clear from the records that the clutch mechanism was not fully functional during these experiments, and although useful data was recovered, the characteristics of the input motion were not ideal. In Figure 4, it can be seen that the motion builds up relatively slowly, and does not terminate cleanly, both indicative of difficulties with the gripping of the clutch.

Following Model 1a, the clutch mechanism was re-examined to improve its performance. Early indications are that this has been successful and future experiments will benefit from this exercise.

4.0 ESB CONTAINER DESIGN

During this period of research, plans were developed to construct at least one new ESB container to enable a more rapid throughput of model experiemtns and to overcome difficulties experienced with the sealing of the first ESB. The original unit was constructed from aluminium alloy 'rings' with layers of a stiff rubber 4mm thick sandwiched between them. The rubber was bonded to the aluminium using glue. Difficulties were experienced early on with leakage under vacuum through this container and measurements of its lateral stiffness suggested that the box was less stiff in shear than expected, based on the stiffness of the rubber aluminium sandwich. It was concluded that the aluminium and rubber sheet were not fully bonded, and this was causing the leakage and low stiffness under lateral shear.

A series of analyses were prepared to provide a basis for the selection of a rubber bonding agent for the new container and to analyse the original ESB container. These are presented in Appendix D, ESB Container Design.

The calculations provide a basis for selecting a rubber stiffness based on the theoretical shear stiffness of a soil layer under a range of effective overburden pressures and at different strain levels. Effective overburden stresses were varied by considering the effects of excess pore pressure development as a percentage of the initial condition, and this is used to degrade the stiffness of the soil.

The first calculation (Earthq05) considered the ESB to be full of saturated sand at 50g, and deduced the ideal lateral shear stiffness of the container accordingly. At mid-depth in the container, it is seen that the small strain shear modulus Go is in excess of 100 MPa, rising to 140 - 150 MPa at the base of the model. Under an excess pore pressure of 60% of the initial effective overburden, this would reduce to around 60-70 MPa and 90-100 MPa respectively.

The second variable is the level of strain in the soil. To accommodate an elastic shear wave the soil is compelled to strain, and the level of strain will depend on the shear stiffness of the soil and the shear stress amplitude of the incoming wave.

There are a number of models for the degradation of soil stiffness with strain amplitude. These generally scale the stiffness as a function of the small strain value. In these calculations, the data presented by the PHRI are used as typical of the classic S curve relating strain level to stiffness. Based on strain amplitude and excess pore pressure, it was then possible to compute the shear stiffness of the soil at mid-depth in the ESB under a wide range of conditions.

The amplitude of the earthquake has a strong influence on the strain level in the soil and using the mass of the ESB and soil above the layer in question (and neglecting amplification for simplicity) a rough estimate may be made of the strain level in the soil column as a function of the shear modulus and the earthquake amplitude.

It was found that there were a range of solutions providing a rough compatibility between ESB stiffness and earthquake amplitude depending on the selection of the level of excess pore pressure. For example, on page 3 of the generic calculation (Earthq05) in Appendix D, there is a solution at 8% amplitude corresponding to a shear modulus of around 10MPa, a shear strain level of around 0.25% and an excess pore pressure of around 60%. Similarly there is a solution at around 6% amplitude corresponding to a shear modulus of 20MPa, a shear strain level of 0.1% and an excess pore pressure of around 60%. The maximum value of earthquake amplitude for which there is a solution is around 16%, with zero excess pore pressure, a stiffness of 20 MPa and a shear strain of 0.25%.

There is no 'absolute' or single correct solution. The experimenter can make a judgement as to the most appropriate level of stiffness for the experiment in hand, but the rate of degradation of stiffness with strain amplitude in the soil means that any choice must take into consideration the likely response of the model. In the ESB, one approach is to consider that the boundaries are far removed from the region of soil-structure interaction of prime interest. In this case it may be appropriate to consider that the soil does not significantly degrade during the event and to work with a somewhat higher stiffness.

In the present experiment series it is the design intent that the full layer of soil at any level in the ESB should behave uniformly and that substantial degradation is expected to take place. Selection of the ESB stiffness in this case will be based largely on judgement and should be matched to a highly softened condition. However, because of the lack of laboratory test data at strain levels above about 0.25% comparisons with large amplitude earthquake motions and highly softened conditions are not straightforward and requires extrapolation.

Appendix D includes specific calculations analysing the 'ideal' stiffness of the ESB for the different models in the current test series. In each case there are a range of solutions as above for different levels of excess pore pressure, and earthquake amplitude.

This approach has provided good insight into the significance of the shear stiffness of the ESB container and how different elastic bonding agents might be selected. A series of experiments using the direct shear box and samples of aluminium plate with different bonding agents are planned and will be used as a basis for selection for the new ESB container.

5.0 CONCLUSIONS

A detailed test plan and experiment design has been completed for the first series of earthquake experiments at WES using the new earthquake actuator and large ESB container. The test plan provides for a range of models upto an initial effective overburden pressure of 10 tsf.

The first experiment in the earthquake series has been satisfactorily carried out and data processed. Extensive liquefaction was observed in the upper layers of the model.

The design of the ESB container has been analysed to provide guidance as to the selection of lateral shear stiffness for new containers, planned for construction at WES.

REFERENCES

PHRI (1997) Handbook on liquefaction remediation of reclaimed land, Balkema.

Seed R B and Harder L F (1990) SPT-Based analysis of cyclic pore pressure generation and undrained residual strength, Proc. H Bolton Seed Memorial Symposium, Vol. 2, pp 351 - 376, BiTech Publishers Ltd, Vancouver.

Steedman R S (1997) Development of a Centrifuge Model Test Program for the study of liquefaction, Final Technical Report, European Research Office of the US Army, London, Contract N68171-97-C-9012.

APPENDIX A

EARTHQUAKE EXPERIMENT SERIES DOCUMENTATION

CATALOGUE OF FILES

EARTHQUAKE EXPERIMENT SERIES DOCUMENTATION

Report	Outline and purpose	Filename
Earthquake Model Test Plan	Describes the initial earthquake models under Series 1 of the EQEN program.	EQTESTPN.DOC
Series 1, Model Design (Ottawa sand)	Calculations presenting design configurations for Models 1 to 5 under Series 1, based on parameters for Ottawa sand.	EARTHQ02.XLS
Earthquake Experiment Series, Model 1a Interpretative Report	Data report describing Model 1a, constructed from Ottawa sand with a vertical effective stress of 1 tsf at mid depth in a loose layer. Includes time histories of all transducers.	EQTEST01.DOC
Earthquake Experiment Series, Model 1a, Factual Report	Data and experiment log for Model 1a, including calculations of shear modulus degradation, locations of transducers, centrifuge test log.	EARTHQ02.XLS
Calibration of accelerometers	Data and processing of accelerometer calibrations	ACCCAL01.XLS
Series 1, Model Design (Nevada sand)	Calculations presenting design configurations for Models 1 to 5 under Series 1, based on parameters for Nevada sand.	EARTHQ04.XLS
ESB Container Design	Calculation of required shear modulus for ESB container for the general case of a saturated sand model 600 mm deep at 50g and a range of excess pore pressures and earthquake amplitudes.	EARTHQ05.XLS
ESB Design, Models 1 & 2, Series 1 (Nevada sand)	Calculations analyse the stiffness of the ESB container under conditions appropriate to Models 1 and 2.	ESBMOD01.XLS
ESB Design, Model 3, Series 1	Calculations analyse the stiffness of the ESB container under conditions appropriate to Model 3 (2 tsf).	ESBMOD03.XLS

ESB Design, Model 4, Series 1	Calculations analyse the stiffness of the ESB container under conditions appropriate to Model 4 (3.2 tsf).	ESBMOD04.XLS
ESB Design, Future recommendations	Discussion and recommendations concerning the design of further ESB containers	to be completed

APPENDIX B

EARTHQUAKE MODEL TEST PLAN

Experiments and Model Design

EARTHQUAKE MODEL TEST PLAN

This plan describes the initial earthquake models under the EQEN program.

Series 1 (K_σ)

1. Outline of experiments

Series 1 comprises a series of experiments investigating the liquefaction of a loose saturated layer under varying effective overburden pressures. The aim of the experiments is to achieve an improved understanding of the K_σ factor in liquefaction analysis through centrifuge model tests of a level, saturated sand bed under strong base shaking. The objective of the series is to capture data of accelerations and excess pore pressures in a loose layer as excess pore pressures reach a condition of initial liquefaction under a range of different initial effective overburden stresses ranging from 1 tsf to 10 tsf. The experiments will be conducted in the Equivalent Shear Beam (ESB) model container using the new earthquake actuator on the WES centrifuge.

2. Summary of Model Test Series

Test	MH	Dr (loose)	σ_v' (KPa)	σ_v' (tsf)	Comments
1	0	35%	108	1	
2	0	35%	108	1	
3	0	35%	215	2	
4	0	35%	350	3.2	
5	0	35%	1070	10	surcharge

Table 1, Summary of Model Test Series 1

Models 1 through 4 will be constructed from medium dense (Dr = 57%) sand, with the loose layer located at an appropriate depth in the model to ensure the target effective overburden pressure is achieved at mid-height in the loose layer. The first model will be constructed with Ottawa sand (Model 1a). Subsequent models (which may include repeats of the initial experiments) will use Nevada sand (Model 1b). Models 1 to 3 will have a phreatic surface at ground level. For Model 4, the phreatic surface will be depressed below the surface to achieve the required effective overburden stress in the loose layer. In Model 5, a surcharge of lead pellets will be required, together with a depressed phreatic surface.

The Model test design is presented in Calculations EARTHQ02.XLS (Ottawa sand) and EARTHQ04.XLS (Nevada sand), attached.

3. Materials

Specific gravity	2.68
Maximum void ratio	0.7633
Minimum void ratio	0.4762
D_{50}	0.12 mm (approx)
D_{10}	0.075 mm (approx)

Table 2a, Ottawa Sand specification (reference)

Specific gravity	2.64
Maximum void ratio	0.756
Minimum void ratio	0.516
D_{50}	0.18 mm (approx)
D_{10}	0.11 mm (approx)

Table 2b, Nevada Sand specification (as measured)

Density	1000 kg/m^3 (assumed)
Viscosity	50 cs
Composition	glycerine-water mix

Table 3, Specification for pore fluid (reference)

Specific gravity	11.3
Nominal particle size	1 mm
Void ratio	0.6 (estimated)

Table 4, Specification of lead pellets (reference)

4. Model specifications

	Models 1 and 2	Model 3	Model 4	Model 5
Description	Saturated, level sand bed with 160 mm deep loose layer at the base of the model	Saturated, level sand bed with 160 mm deep loose layer at the base of the model	Saturated, level sand bed with 160 mm deep loose layer at the base of the model and a depressed phreatic surface	Saturated, level sand bed with a 160 mm deep loose sand layer overlain by a layer of denser sand and a surcharge of lead pellets
Dry density of surcharge	none	none	none	7064 kg/m^3 (441.0 pcf)
Sand dry density (upper)	1672 kg/m^3 (104.4 pcf)	1672 kg/m^3 (104.4 pcf)	1672 kg/m^3 (104.4 pcf)	1672 kg/m^3 (104.4 pcf)
Sand dry density (loose layer)	1611 kg/m^3 (100.6 pcf)	1611 kg/m^3 (100.6 pcf)	1611 kg/m^3 (100.6 pcf)	1611 kg/m^3 (100.6 pcf)
Pore fluid	glycerine solution	glycerine solution	glycerine solution	glycerine solution
Viscosity	50 cs	50 cs	50 cs	50 cs
g level at 6 m	50	50	50	50
Thickness of surcharge	none	none	none	290 mm
Thickness of upper sand layer	140 mm	365 mm	420 mm	110 mm
Depth of phreatic surface	0 mm	0 mm	380 mm	270 mm
Effective vertical stress at mid-depth in loose layer	107.7 KPa (1 tsf)	214.8 KPa (2 tsf)	348.8 KPa (3.25 tsf)	1072.3 KPa (10.0 tsf)
Thickness of base filter layer (dense coarse sand)	16 mm	16 mm	16 mm	16 mm
Total depth of model	316 mm	541 mm	596 mm	596 mm
Total mass of model (saturated)	161.8 kg	278.1 kg	270.6 kg	701.8 kg

Table 5, Model Test specification

A summary of the model test specifications is presented in Table 5. Detailed calculations are attached. These relate to Ottawa sand. Separate calculations will be necessary for Nevada sand. The calculations include estimates of shear modulus and damping in the loose layer as a function of strain level (though not excess pore pressure) and details of the dry and saturated weights of the different layers in the specimen.

5. Instrumentation layout

Attached figure 1 presents sections through Models 1 and 2 showing proposed instrumentation positions. Coordinates x, y, z are defined from the bottom corner of the ESB container, as shown in the attached figures.

Transducer	x (mm)	y (mm)	z (mm)	comment
PPT	250	195	105	
PPT	750	195	105	
PPT	400	195	255	
ACC	250	120	40	
ACC	550	120	40	
ACC	250	120	105	
ACC	550	120	105	
ACC	250	120	185	
ACC	550	120	185	
ACC	250	120	255	
ACC	550	120	255	
ACC	250	120	310	
ACC	550	120	310	
ACC	ESB container		base plate	horizontal
ACC	ESB container		base plate	vertical
ACC	ESB container		105 (to suit)	horizontal
ACC	ESB container		255 (to suit)	horizontal

Table 6, Instrumentation layout, Models 1 and 2

6. Experiment plan

Each model is constructed by dry pluviation and saturated under vacuum. Locations of instruments are measured after placement and again (by excavation) after the model test is completed.

After saturation the ESB container is positioned onto the shaking table of the earthquake actuator and the centrifuge is accelerated to 50g (in stages, if required).

At 50g, after static readings of the pore pressure transducers (and LVDTs, if used) a single earthquake is fired using the 1.47 mm amplitude rocker arm to generate a 5.3g input base motion (10.6%), subject to full clutch engagement. Using the electric motor drive, the input motion will be at 30 Hz. The duration of the excitation must be selected accordingly, but should be at least 600 ms (18 cycles). Experience shows that the platform continues to vibrate after the clutch has nominally disengaged. Data recording periods should be selected accordingly, but should be at least twice the duration of shaking at high frequency.

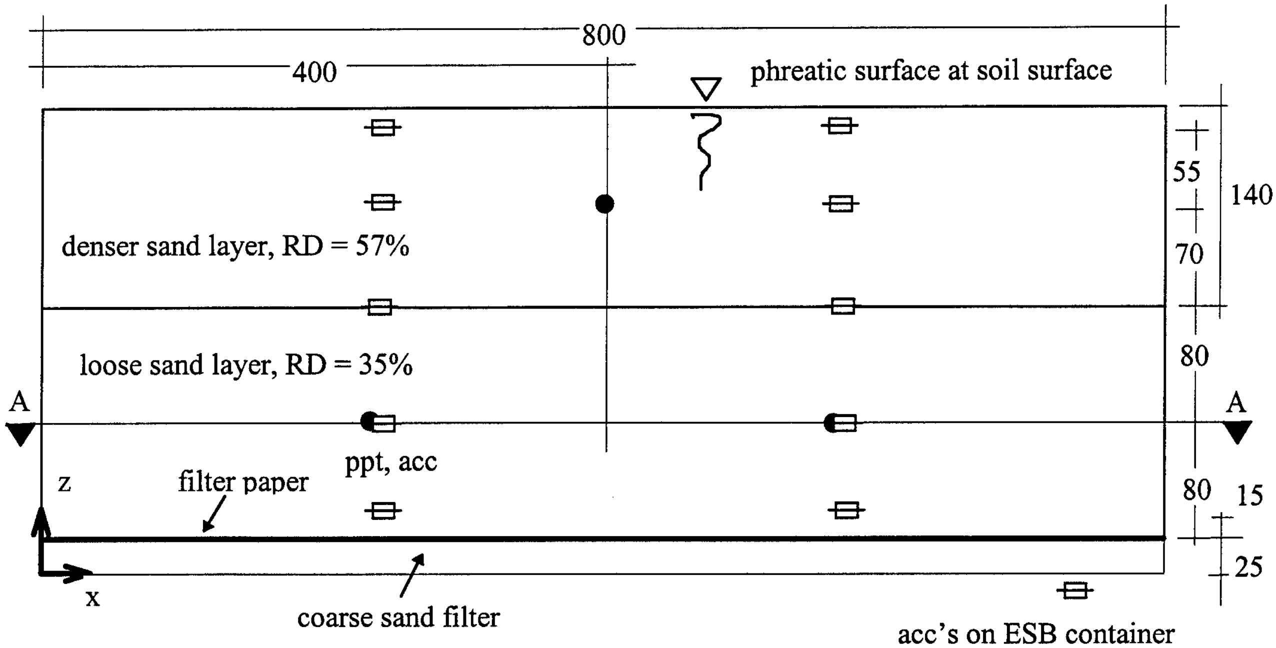
Data of pore pressure response should also be recorded over several seconds after the shaking event, to capture the post-earthquake dissipation of excess pore pressure. This may be at a lower data capture rate.

Depending on the data of pore pressure development, a second earthquake will be triggered at 30g, under which the input motion would correspond to 17.7%.

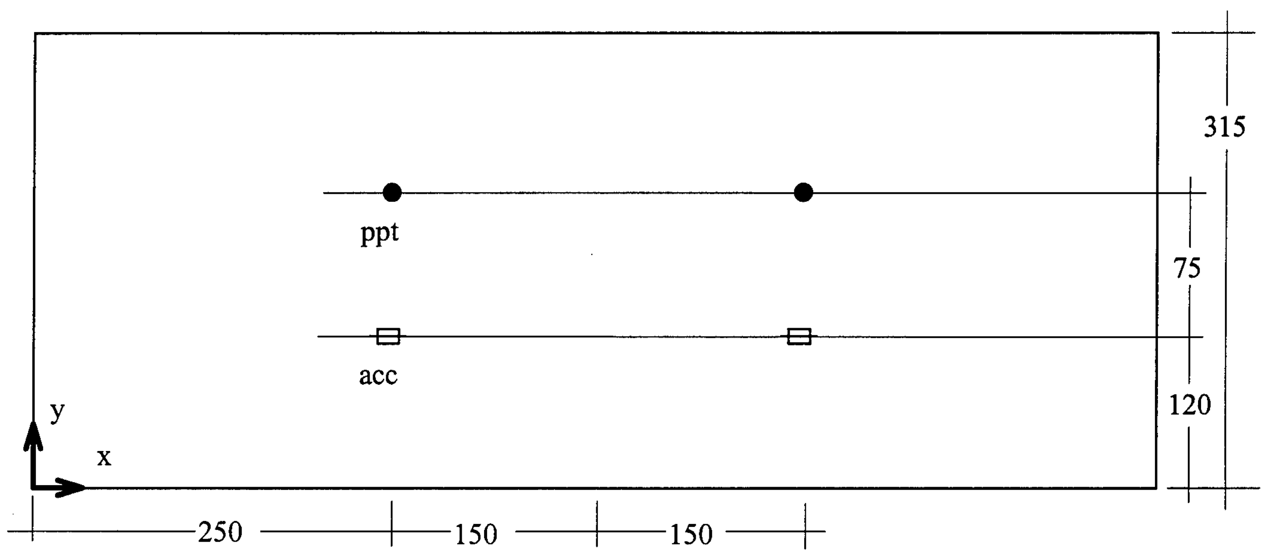
In the event that insufficient energy is imparted to the model, even with full clutch engagement, the 4.41 mm amplitude rocker arm will be used, which will generate 16g base input motion, or 31.9% at 50g.

RSS

prepared	13 November 1997
last updated	7 January 1998



Cross-section through model



Plan on section A-A

Figure 1, Models 1 and 2, vertical effective stress on A-A = 1 tsf (dimensions in mm)

SERIES 1 MODEL DESIGN (OTTAWA SAND)
SUMMARY

The attached worksheets present a series of calculations concerning the design of the first models for Series 1 under the EQEN test series using parameters appropriate to Ottawa sand.

The idealised models are developed, using data for Nevada sand and considering 4 different cross-sections, each selected to achieve a different initial effective vertical stress at mid-depth in a 160 mm deep loose layer near the bottom of the ESB container. For each model layout, the theoretical small strain shear modulus is calculated and degraded as a function of strain. The masses of soil and fluid in each layer are computed. In Model 5, because of the high overburden requirement which conflicts with the depth of the container at 50g, lead pellets are used to form a deep upper layer. An outline of the models is presented in the word document entitled Earthquake Model Test Plan EQTESTPN.DOC.

The layout for 'Models 1 & 2' was used as the target layout for Model 1a.

Series 1, Earthquake model design (Ottawa sand)

ESB container	Depth	600	mm
Loose layer thickness		160	mm

Ottawa Sand		
Maximum void ratio	0.797	
Minimum void ratio	0.505	
Specific gravity	2.68	
Loose Relative density	35%	
Void ratio	0.695	
Dry weight	15.5	KN/m^3
Bouyant weight	9.7	KN/m^3
Saturated weight	19.5	KN/m^3
Dense Relative density	57%	
Void ratio	0.63	
Dry weight	16.1	KN/m^3
Bouyant weight	10.1	KN/m^3
Saturated weight	19.9	KN/m^3
Ottawa sand D_{50} (approx)	0.12	mm
Ottawa sand D_{10} (approx)	0.075	mm

Surcharge (lead pellets) - not used		
Specific gravity	11.3	
Void ratio	0.6	
Dry weight	69.3	KN/m^3
Bouyant weight	63.2	KN/m^3
Saturated weight	73.0	KN/m^3

Coarse sand for base layer 4		
Specific gravity	2.65	
Relative density	80%	
Void ratio	0.5	
Dry weight	17.3	KN/m^3
Bouyant weight	10.8	KN/m^3
Saturated weight	20.6	KN/m^3

		Models 1&2	Model 3	Model 4	Model 5	
Nominal g at	6 m	50	50	50	50	gravities
Layer 1 centroid		5.7275	5.613	5.589	5.534	m
Layer 2 centroid		5.799	5.799	5.799	5.744	m
Loose Layer centroid		5.879	5.879	5.879	5.879	m
Layer 4 centroid		5.967	5.967	5.967	5.967	m
Layer 1 (sand, lead pellets for Model 5)						
Depth to wt		0	0	380	270	mm
Depth below wt		143	372	40	40	mm
Effective surcharge		69.0	175.9	304.3	979.2	KPa
Layer 2 (sand)						
Depth below wt		0	0	0	110	mm
Effective surcharge		0.0	0.0	0.0	53.2	KPa
Layer 3 (loose sand)						
Depth to middle of layer below surcharge		80	80	80	80	mm
Total depth to middle of loose layer		223	452	500	500	mm
Equivalent depth (approximate)		11.4	23.3	37.6	34.2	m
σ_v'		107.1	214.0	342.4	1070.5	KPa
or σ_v'		1.00	2.00	3.19	9.98	tsf
Ko		0.5	0.5	0.5	0.5	
σ_m'		71.4	142.7	228.3	713.7	KPa
Go (round particles) at middle of loose layer		75190	106286	134431	237697	KPa
Go (angular particles)		84547	119513	151161	267278	KPa
Layer 4 (dense coarse sand)						
Thickness		16	16	16	16	mm
Depth check (to be less than 600)		319	548	596	596	mm

Earthquake model design, calculation 2 contd.

Data from Table 4.10 of shear modulus for sands, angular particles, ref 1

Strain amp	A	n	Strain %	$G_{1,2}$	G_3	G_4	G_5
10^{-6}	1	0	0.0001	84547	119513	151161	267278
10^{-5}	0.93	0.01	0.001	78380	111565	141772	253552
5×10^{-5}	0.83	0.03	0.005	69509	100318	128684	235451
10^{-4}	0.75	0.05	0.01	62413	91332	118263	221373
2.5×10^{-4}	0.56	0.1	0.025	45868	69485	92113	182537
5×10^{-4}	0.43	0.16	0.05	34556	54569	74408	157888
10^{-3}	0.3	0.22	0.1	23655	38938	54612	124085
2.5×10^{-3}	0.15	0.3	0.25	11531	20062	29215	72719

Data from Table 4.12 for damping factor h for sands, ref 1

Strain amp	$h_{average}$	$h_{maximum}$	$h_{minimum}$	Strain amplitude (%)	Average damping (%)
10^{-6}	0.026	0.04	0.016	0.0001	2.6
10^{-5}	0.03	0.04	0.018	0.001	3.0
5×10^{-5}	0.033	0.042	0.02	0.005	3.3
10^{-4}	0.037	0.048	0.026	0.01	3.7
2.5×10^{-4}	0.055	0.068	0.04	0.025	5.5
5×10^{-4}	0.08	0.098	0.06	0.05	8.0
10^{-3}	0.12	0.145	0.092	0.1	12.0
2.5×10^{-3}	0.174	0.2	0.148	0.25	17.4

Ref 1: Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997, p64.

ESB container dimensions	Width	315 mm		
	Length	800 mm	Area	0.252 m^2

Depths	Models 1&2	Model 3	Model 4	Model 5
Depth of layer 1 above water table	0	0	380	270
Depth of layer 1 below water table	143	372	40	40
Depth of layer 2	0	0	0	110
Depth of loose layer	160	160	160	160
Depth of layer 4 (porous plates)	16	16	16	16
Total depth in ESB container	319	548	596	596

	Models 1&2		Model 3		Model 4		Model 5	
Mass per layer	kg	lbs	kg	lbs	kg	lbs	kg	lbs
Layer 1 total mass	73.2	161.3	190.4	419.7	177.9	392.2	555.5	1224.7
Layer 1 dry mass	59.2	130.6	154.1	339.8	174.0	383.6	551.7	1216.3
Layer 2 total mass	0.0	0.0	0.0	0.0	0.0	0.0	56.3	124.1
Layer 2 dry mass	0.0	0.0	0.0	0.0	0.0	0.0	45.6	100.5
Layer 3 total mass	80.3	177.0	80.3	177.0	80.3	177.0	80.3	177.0
Layer 3 dry mass	63.8	140.5	63.8	140.5	63.8	140.5	63.8	140.5
Layer 4 total mass	8.5	18.7	8.5	18.7	8.5	18.7	8.5	18.7
Layer 4 dry mass	7.1	15.7	7.1	15.7	7.1	15.7	7.1	15.7
Total mass of pore fluid	31.8	70.1	54.1	119.3	21.8	48.0	32.4	71.4
Total mass of model	161.9	357.0	279.1	615.3	266.7	587.9	700.5	1544.4

SERIES 1 MODEL DESIGN (NEVADA SAND)
SUMMARY

The attached worksheet present a series of calculations concerning the design of the models for Series 1 under the EQEN test series using parameters appropriate to Nevada sand.

The idealised models are developed, using data for Nevada sand and considering 4 different cross-sections, each selected to achieve a different initial effective vertical stress at mid-depth in a 160 mm deep loose layer near the bottom of the ESB container. For each model layout, the theoretical small strain shear modulus is calculated and degraded as a function of strain. The masses of soil and fluid in each layer are computed. In Model 5, because of the high overburden requirement which conflicts with the depth of the container at 50g, lead pellets are used to form a deep upper layer. An outline of the models is presented in the word document entitled Earthquake Model Test Plan EQTESTPN.DOC.

The calculation is based on calculation EARTHQ02.XLS.

Series 1, Earthquake model design (Nevada sand)
This calculation is based on earthq02.xls for Ottawa sand

ESB container	Depth	600 mm
Loose layer thickness		160 mm

Calculation assumes base plate and two porous plates (only) in bottom of ESB container

Nevada sand	
Maximum void ratio	0.756
Minimum void ratio	0.516
based on measured values of 93.8 and 108.7 lb/ft^3	
Specific gravity	2.64
Loose Relative density	35%
Void ratio	0.673
Dry weight	15.5 KN/m^3
Bouyant weight	9.6 KN/m^3
Saturated weight	19.4 KN/m^3
Dense Relative density	57%
Void ratio	0.62
Dry weight	16.0 KN/m^3
Bouyant weight	9.9 KN/m^3
Saturated weight	19.7 KN/m^3
Nevada sand D_{50} (approx)	0.18 mm
Nevada sand D_{10} (approx)	0.11 mm

Surcharge (lead pellets) - used in Model 5	
Specific gravity	11.3
Void ratio	0.6
Dry weight	69.3 KN/m^3
Bouyant weight	63.2 KN/m^3
Saturated weight	73.0 KN/m^3

Base materials (assumed aluminium)	
Dry weight	27.0 KN/m^3
Bouyant weight	17.0 KN/m^3
Saturated weight	27.0 KN/m^3

		Models 1&2	Model 3	Model 4	Model 5	
Nominal g at	6 m	50	50	50	50	gravities
Layer 1 centroid		5.6975	5.579	5.561	5.5085	m
Layer 2 centroid		5.771	5.771	5.771	5.7185	m
Loose Layer centroid		5.851	5.851	5.851	5.851	m
Layer 4 centroid		5.9405	5.9405	5.9405	5.9405	m
Upper layer (sand, lead pellets for Model 5)						
Depth to wt		0	0	400	255	mm
Depth below wt		147	384	20	60	mm
Effective surcharge		69.3	177.3	305.5	984.9	KPa
Middle layer (sand) used for Model 5						
Depth below wt		0	0	0	105	mm
Effective surcharge		0.0	0.0	0.0	49.7	KPa
Loose sand layer)						
Depth to middle of layer below surcharge		80	80	80	80	mm
Total depth to middle of loose layer		227	464	500	500	mm
Equivalent depth (approximate)		11.6	23.8	38.3	33.7	m
σ_v'		106.8	214.8	343.1	1072.1	KPa
or σ_v'		1.00	2.00	3.20	10.00	tsf
Ko		0.5	0.5	0.5	0.5	
σ_m'		71.2	143.2	228.7	714.8	KPa
Go (round particles) at middle of loose layer		78360	111119	140424	248248	KPa
Go (angular particles)		87201	123656	156268	276257	KPa
Layer 4 half inch base plate, two 1/8" porous plates						
Thickness		19	19	19	19	mm
Depth check (to be less than 600)		326	563	599	599	mm

Earthquake model design, calculation contd.

Data from Table 4.10 of shear modulus for sands, angular particles, ref 1

Strain amp	A	n	Strain %	$G_{1,2}$	G_3	G_4	G_5
10^{-6}	1	0	0.0001	87201	123656	156268	276257
10^{-5}	0.93	0.01	0.001	80838	115436	146565	262073
5×10^{-5}	0.83	0.03	0.005	71686	103807	133040	243372
10^{-4}	0.75	0.05	0.01	64363	94514	122270	228827
2.5×10^{-4}	0.56	0.1	0.025	47295	71919	95243	188697
5×10^{-4}	0.43	0.16	0.05	35626	56493	76945	163232
10^{-3}	0.3	0.22	0.1	24382	40319	56480	128297
2.5×10^{-3}	0.15	0.3	0.25	11883	20780	30219	75196

Data from Table 4.12 for damping factor h for sands, ref 1

Strain amp	$h_{average}$	$h_{maximum}$	$h_{minimum}$	Strain amplitude (%)	Average damping (%)
10^{-6}	0.026	0.04	0.016	0.0001	2.6
10^{-5}	0.03	0.04	0.018	0.001	3.0
5×10^{-5}	0.033	0.042	0.02	0.005	3.3
10^{-4}	0.037	0.048	0.026	0.01	3.7
2.5×10^{-4}	0.055	0.068	0.04	0.025	5.5
5×10^{-4}	0.08	0.098	0.06	0.05	8.0
10^{-3}	0.12	0.145	0.092	0.1	12.0
2.5×10^{-3}	0.174	0.2	0.148	0.25	17.4

Ref 1: Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997, p64.

ESB container dimensions	Width	300 mm (315 -15mm for the glass plates)		
	Length	800 mm	Area	0.24 m^2

Depths	Models 1&2	Model 3	Model 4	Model 5
Depth of layer 1 above water table	0	0	400	255
Depth of layer 1 below water table	147	384	20	60
Depth of layer 2	0	0	0	105
Depth of loose layer	160	160	160	160
Depth of layer 4 (porous plates)	19	19	19	19
Total depth in ESB container	326	563	599	599

	Models 1&2		Model 3		Model 4		Model 5	
Mass per layer	kg	lbs	kg	lbs	kg	lbs	kg	lbs
Layer 1 total mass	71.0	156.5	185.5	408.9	166.1	366.2	539.3	1189.0
Layer 1 dry mass	57.5	126.8	150.2	331.1	164.3	362.1	533.9	1177.1
Layer 2 total mass	0.0	0.0	0.0	0.0	0.0	0.0	50.7	111.8
Layer 2 dry mass	0.0	0.0	0.0	0.0	0.0	0.0	41.1	90.5
Layer 3 total mass	76.0	167.6	76.0	167.6	76.0	167.6	76.0	167.6
Layer 3 dry mass	60.6	133.6	60.6	133.6	60.6	133.6	60.6	133.6
Layer 4 total mass	12.6	27.7	12.6	27.7	12.6	27.7	12.6	27.7
Layer 4 dry mass	12.6	27.7	12.6	27.7	12.6	27.7	12.6	27.7
Total mass of pore fluid	28.9	63.8	50.7	111.8	17.3	38.1	30.5	67.2
Glass plates								
Total mass of model	159.6	351.8	274.1	604.2	254.7	561.5	678.6	1496.1

Empty container mass
Total mass of ESB

APPENDIX C

EARTHQUAKE EXPERIMENT SERIES

MODEL 1a

INTERPRETATIVE AND FACTUAL REPORTS

EARTHQUAKE EXPERIMENT SERIES
MODEL 1a
INTERPRETATIVE REPORT

This report is one of a series describing the preparation and testing of the models completed for Series 1 of the EQEN program. This report should be read in conjunction with the Factual Report for Model 1a.

Background to Series 1 (K_σ)

1. Outline of experiments

Series 1 comprises a series of experiments investigating the liquefaction of a loose saturated layer under varying effective overburden pressures. The aim of the experiments is to achieve an improved understanding of the K_σ factor in liquefaction analysis through centrifuge model tests of a level, saturated sand bed under strong base shaking. The objective of the series is to capture data of accelerations and excess pore pressures in a loose layer as excess pore pressures reach a condition of initial liquefaction under a range of different initial effective overburden stresses ranging from 1 tsf to 10 tsf. The experiments will be conducted in the Equivalent Shear Beam (ESB) model container using the new earthquake actuator on the WES centrifuge.

2. Summary of Model Test Series

Each test series includes one or more experiments. Model 1a was designed in accordance with the specifications for Test 1, Table 1.

Test	MH	Dr (loose)	σ_v' (KPa)	σ_v' (tsf)	Comments
1	0	35%	108	1	
2	0	35%	108	1	
3	0	35%	215	2	
4	0	35%	350	3.25	
5	0	35%	1070	10	surcharge

Table 1, Summary of Model Test Series 1

Introduction

This report presents data and discussion relating to the first model experiment, identified as Model 1a. The aim of the experiment was to develop model preparation techniques and to confirm that shaking using the new large shaker could generate a series of cycles of roughly uniform amplitude leading to liquefaction in a soil specimen under an initial condition of 1 tsf vertical effective stress. The Earthquake Model Test Plan presents more information about the range of Tests under Series 1. The model design is presented in a separate report (Series 1, Model Design (Ottawa sand)) in detail, and the as built records, data and experiment log are presented in the Model 1a Factual Report.

Overview of Model 1a

The model was built using Ottawa sand with a loose layer at the base of the container and a denser layer above. The ESB container was not full of sand, as with the loose layer on the bottom of the container the overlying layer was only required to be around 140 mm deep to achieve the target of 1 tsf vertical effective stress at mid-depth in the loose layer.

As placed, the loose layer had a relative density of 52%, compared with a target relative density of 35%. The overlying denser layer was at around 70%, also in excess of the target of 57%. Techniques for sand placing were reviewed following this experiment.

A pore fluid comprising a mixture of water and glycerine was used to increase its viscosity to around 50 times that of water alone.

Three pore pressure transducers (ppt) were located in the model, two at mid-depth in the loose layer and the third around mid-depth in the upper denser layer. All three devices functioned well, both during acceleration to 50g and during the two episodes of base shaking to which the specimen was subjected.

The model showed liquefaction during both earthquakes, despite the generally low level of shaking (around 5% input motion). The liquefaction front advanced from the surface downwards, but did not reach the middle of the loose layer in either event, although excess pore pressure development in the loose layer reached at least 30-40% of the initial effective vertical stress. The upper layer was liquefied after 10 cycles of shaking in earthquake 1 (base input around +/- 3%, rising to +/- 8%) and around 13 cycles in earthquake 2 (base input around +/- 3% peak in loose layer).

Data records

The time histories of acceleration and pore pressure development at each of the transducers during the two episodes of base shaking are presented in the Factual Report. Only one accelerometer malfunctioned (ACC 7726 at the base of the loose layer) but a second device at the same depth functioned satisfactorily. The three pore pressure transducers showed good response, both during acceleration to 50g and during the shaking. Their calibration was established by measurement. The calibration for one of the accelerometers (ACC 1925) has had to be estimated, but this is not considered to impart a significant error. All other accelerometers were calibrated after the experiment. The pore fluid solution was mixed to a viscosity of 50 times that of water, but this was not confirmed by measurement.

The data are presented in engineering units, in real time. Thus accelerations are presented as a percentage of 50g, and excess pore pressures are given in KPa. The shaking may be seen to occur with a fundamental period of around 37 milliseconds, indicating a frequency of around 27 Hz. In field terms, this would be equivalent to 27/50 = 0.54 Hz.

Earthquake 1

The first earthquake comprised upwards of twenty cycles of shaking, starting with around 12 cycles building quickly to +/- 3% g (measured on the ESB container just above the base), followed by at least seven cycles at around +/- 8%. In the sand column, motions at the base of the loose layer peaked at around +/- 7% (with most of the energy at around +/- 5%) and this

was amplified through the model to levels in excess of +/- 10%, although records from near the surface of the sand showed smaller levels caused by the extensive liquefaction of the upper sand layer. This is also reflected in the acceleration time histories from the top of the upper sand layer, which show motions typical of a soil largely isolated from the shaking below, but with occasional high amplitude 'peaky' motion characteristic of a snatching mechanism in the soil as the particles momentarily re-engage (see for example ACC 5754, earthquake 1.

The long duration of the shaking was caused by a double triggering of the clutch mechanism and it is considered that this also contributed to the larger magnitude of the later cycles. However high frequency data capture was terminated after 1 second, at which time the excess pore pressures in the loose sand layer were still rising (see PPT 9 and PPT 10, earthquake 1). The level of excess pore pressure reached at the end of the record is estimated to be of the order of 30-40%. The peak value reached is not known. In the upper, denser layer, liquefaction can be seen after only 10-12 cycles, with the characteristic double frequency cycling associated with a 'butterfly' stress path under near zero effective stress conditions (PPT 31).

Earthquake 2

In earthquake 2 the clutch was triggered once, for a nominal 300 ms period (as for earthquake 1) but video records show clearly that the clutch did not disengage immediately, and this may account for the continuing shaking with time up to the full 1 second period of data capture.

Input motion for earthquake 2 peaked after around 7-8 cycles at about +/- 3% although this was more than sufficient to liquefy the upper sand layer again (see PPT 31). In the loose layer, it is estimated that excess pore pressures reached only around 5-10% of the initial effective vertical stress.

Conclusions and recommendations

This first model experiment confirmed that the new earthquake actuator is well suited to generating a sequence of defined cycles of shaking motion. The shaker control systems and data aquisition arrangements proved satisfactory, and useful data was achieved.

Background vibration from the shaker and electrical noise levels were small, and did not interfere with the data capture.

Further work is required to improve the performance of the clutch mechanism, which will improve the uniformity and 'shape' of the shaking cycles.

It is recommended that the data window is substantially increased for future experiments, and that the duration of clutch engagement is also increased to 1200 ms. The duration of sampling should be increased to 2 seconds, although this may necessitate a reduction in the frequency of sampling.

RSS
7 January 1998

EARTHQUAKE EXPERIMENT SERIES
MODEL 1a
AS BUILT DATA AND EXPERIMENT RECORD
FACTUAL REPORT

This report presents data and calculations concerning the completion of Model 1a, Series 1 under the EQEN test series.

All data relevant to the experiment is presented, including material parameters, as built model details, transducer locations, pore pressure readings and time histories.

This worksheet should be read in conjunction with the Interpretative Report for Model 1a (EQTEST01.DOC).

Series 1, Model 1a (Ottawa sand), as built data and experiment record
Factual Report

ESB container	Depth	600	mm
Loose layer thickness		160	mm

Ottawa Sand			
Maximum void ratio	93.1	0.79706	
Minimum void ratio	111.2	0.50456	
Specific gravity		2.68	
Loose Relative density		52.3%	
Void ratio		0.644	
Dry weight		16.0	KN/m^3
Bouyant weight		10.0	KN/m^3
Saturated weight		19.8	KN/m^3
Dense Relative density		69.6%	
Void ratio		0.593	
Dry weight		16.5	KN/m^3
Bouyant weight		10.3	KN/m^3
Saturated weight		20.2	KN/m^3
Ottawa sand D_{50} (approx)		0.12	mm
Ottawa sand D_{10} (approx)		0.075	mm

Coarse sand for base layer		
Specific gravity	2.65	est
Relative density	50%	est
Void ratio	1.032	
Dry weight	12.8	KN/m^3
Bouyant weight	8.0	KN/m^3
Saturated weight	17.8	KN/m^3

		Model 1a		Excess pore pressure 20%	40%	60%
Nominal g at	6 m	50	gravities			
Upper layer centroid		5.769	m			
Loose Layer centroid		5.879	m			
Base layer centroid		5.967	m			
Upper, dense sand layer						
Depth to wt		0	mm			
Depth below wt		140	mm			
Effective surcharge		69.6	KPa			
Loose sand layer						
Depth to middle of layer below surcharge		80	mm			
Total depth to middle of loose layer		220	mm			
Equivalent depth (approximate)		11.2	m			
σ_v'		108.9	KPa	87.12	65.34	43.56
or σ_v'		1.02	tsf	0.81	0.61	0.41
Ko		0.5		0.5	0.5	0.5
σ_m'		72.6	KPa	58.1	43.6	29.0
Go (round particles) at middle of loose layer		83664	KPa			
Go (angular particles)		91872	KPa	82173	71164	58105
Base sand layer						
Thickness		16	mm			
Total height of model in ESB container		316	mm			

Typical strain degradation for as placed loose layer, mid-depth
(as function of strain level and excess pore pressure development)

Strain amp	A	n	Strain %	G	20%	40%	60%
10^{-6}	1	0	0.0001	91872	82173	71164	58105
10^{-5}	0.93	0.01	0.001	85185	76191	65984	53875
5×10^{-5}	0.83	0.03	0.005	75569	67591	58536	47794
10^{-4}	0.75	0.05	0.01	67876	60710	52577	42929
2.5×10^{-4}	0.56	0.1	0.025	49925	44654	38671	31575
5×10^{-4}	0.43	0.16	0.05	37650	33675	29163	23812
10^{-3}	0.3	0.22	0.1	25798	23074	19983	16316
2.5×10^{-3}	0.15	0.3	0.25	12592	11263	9754	7964

Ref: Table 4.10, Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997.

ESB container dimensions		
	Width	315 mm (no glass plates in Model 1a)
	Length	795 mm
	Area	0.250425 m^2

Materials

Base layer sand	Runyon sand, -10 sieve, +40 sieve
Loose layer	Ottawa sand
Dense layer	Ottawa sand

Depths as placed	Model 1a
Depth of upper layer above water table	0 mm
Depth of upper layer below water table	140 mm
Depth of loose layer	160 mm
Depth of base layer (filter sand)	25 mm (no filter paper in Model 1a)
Total depth in ESB container	325 mm

Mass, density per layer as placed	kg	lbs	kg/m3	void ratio
Upper layer total mass	72.0	158.8		
Upper layer dry mass	59.0	**130.0**	1681.9	0.593
Loose layer total mass	81.0	178.6		
Loose layer dry mass	65.3	**144.0**	1630.2	0.644
Filter layer total mass	7.3	16.0		
Filter layer dry mass	8.2	**18.0**	1304.1	1.032
Total mass of pore fluid	27.8	61.4		
Total mass of model	160.3	353.4		

Instrumentation locations
x,y,z in mm defined from base corner of box, Figure 1.
Depth measured by tape from straight edge to top of device.

		ch	depth	centreline	x	y	z
Coords as placed:							
ACC, above base layer	7318	3	575	-175	225	115	25
ACC, above base layer	7726	6	575	145	545	115	25
ACC, mid loose layer	7771	5	488	-150	250	120	112
ACC, mid loose layer	7828	10	488	155	555	120	112
PPT, mid loose layer	PPT10		490	-150	250	200	110
PPT, mid loose layer	PPT9		490	150	550	200	110
ACC, top of loose layer	5756	7	411	-150	250	120	189
ACC, top of loose layer	7706	12	411	148	548	120	189
ACC, mid upper layer	6835	4	342	-150	250	120	258
ACC, mid upper layer	7709	13	342	150	550	120	258
PPT, mid upper layer	PPT31		342	0	400	197	258
ACC, top upper layer	5754	8	292	-150	250	120	308
ACC, top upper layer	3457	11	293	150	550	120	307
ACC, box left ring 2	7314	1 horizontal			0 (nom)	163	79
ACC, box left ring 5	1925	2 horizontal			0 (nom)	163	241
ACC, box right base plate	7319	14 vertical			800 (nom)	na	0

		ch	depth	centreline	x	y	z
Coords on excavation:							
ACC, above base layer	7318	3	566	-180	220	111	34
ACC, above base layer	7726	6	560	158	558	105	40
ACC, mid loose layer	7771	5	515	-155	245	110	85
ACC, mid loose layer	7828	10	505	165	565	120	95
PPT, mid loose layer	PPT10		485	-160	240	195	115
PPT, mid loose layer	PPT9		490	165	565	206	110
ACC, top of loose layer	5756	7	451	-145	255	110	149
ACC, top of loose layer	7706	12	449	155	555	125	151
ACC, mid upper layer	6835	4	389	-157	243	115	211
ACC, mid upper layer	7709	13	395	155	555	116	205
PPT, mid upper layer	PPT31		328	0	400	209	272
ACC, top upper layer	5754	8	344	-96	304	73	256
ACC, top upper layer	3457	11	316	150	550	102	284
ACC, box left ring 2	7314	1 horizontal			0 (nom)	163	79
ACC, box left ring 5	1925	2 horizontal			0 (nom)	163	241
ACC, box right base plate	7319	14 vertical			800 (nom)	na	0

Instrumentation scans

Note: Only PPTs are reproduced here; ACC scans showed zero readings under static conditions.

	jb2	rpm	ch2 PPT10 Volts	ch4 PPT9 Volts	ch6 PPT31 Volts
4 Dec 97, 09.16	1g	0	0.051	-0.044	0.809
	10g	39.24	0.322	0.215	1.083
	20g	54.71	0.63	0.51	1.399
	30g	68.25	0.959	0.833	1.726
	40g	77.68	1.264	1.129	2.032
	50g	86.66	1.567	1.423	2.329
Datafile EQR1_1.TXT	50g	86.62	1.562	1.422	2.428
4 Dec 97, 09.50	1g	0	0.062	-0.007	0.814
4 Dec 97, 10.18	1g	0	0.061	-0.028	0.83
	10g	39.31	0.324	0.219	1.105
	30g	68.12	0.939	0.811	1.747
	50g	86.55	1.55	1.404	2.389
Datafile EQR1_2.TXT	50g	86.54	1.562	1.417	2.406
4 Dec 97, 10.26	1g	0	0.06	-0.008	0.816

Processed data	jb2		ch2 PPT10	ch4 PPT9	ch6 PPT31
calibration (mV/V/psi)			0.174	0.165	0.67
supply (V)			5	5	5
amplifiers			100	100	100
CDAQS gain (measured)			0.935	0.9395	0.943
		rpm	KPa	KPa	KPa
4 Dec 97, 09.16	1g	0	0.0	0.0	0.0
	10g	39.24	23.0	23.0	6.0
	20g	54.71	49.1	49.3	12.9
	30g	68.25	77.0	78.0	20.0
	40g	77.68	102.8	104.3	26.7
	50g	86.66	128.5	130.5	33.2
Datafile EQR1_1.TXT	50g	86.62	128.1	130.4	35.3
4 Dec 97, 09.50	1g	0	0.9	3.3	0.1
4 Dec 97, 10.18	1g	0	0.0	0.0	0.0
	10g	39.31	22.3	22.0	6.0
	30g	68.12	74.4	74.6	20.0
	50g	86.55	126.2	127.4	34.0
Datafile EQR1_2.TXT	50g	86.54	127.2	128.5	34.4
4 Dec 97, 10.26	1g	0	-0.1	1.8	-0.3

EXCEL spreadsheets for earthquake data are eqr1_1 and eqr1-2; figures are attached.

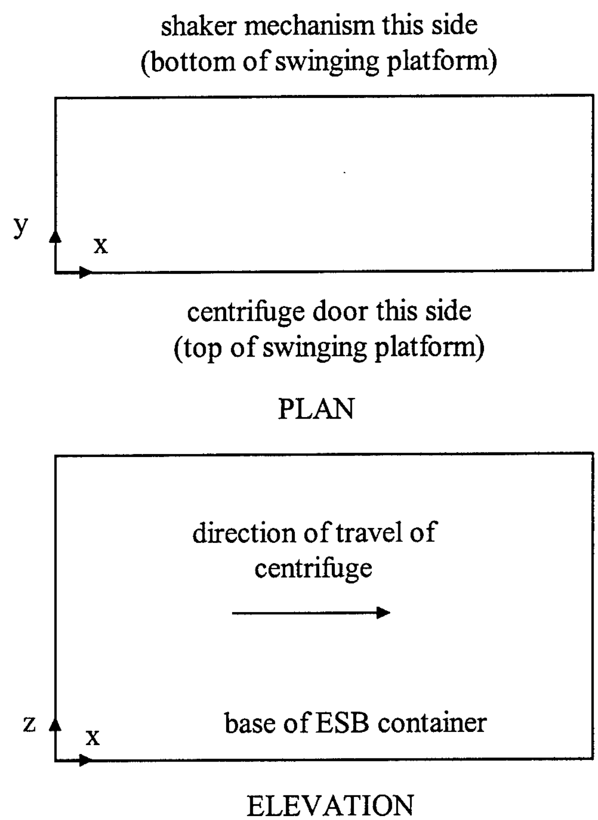
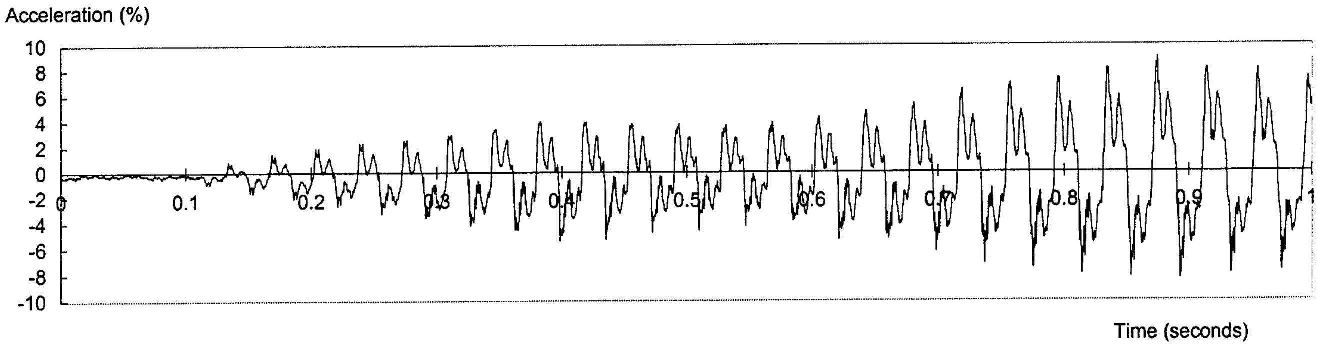
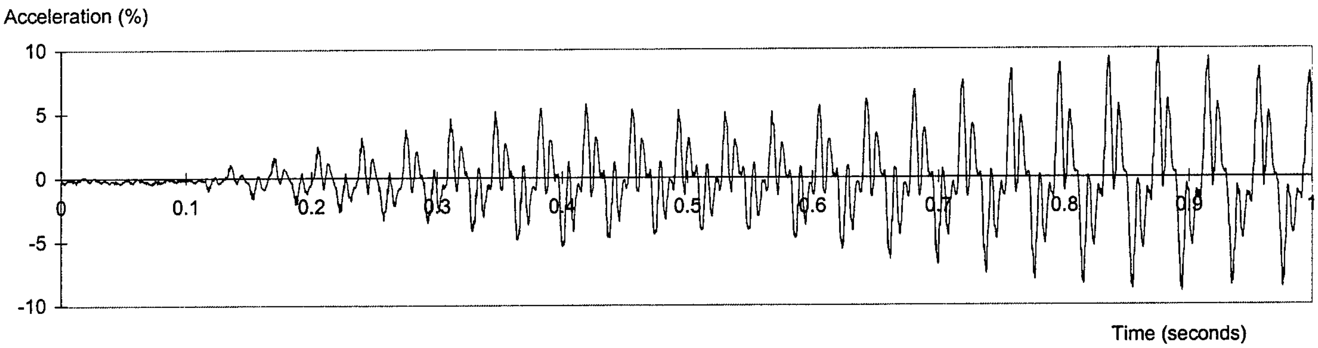


Figure 1 Definition of coordinate system for ESB container

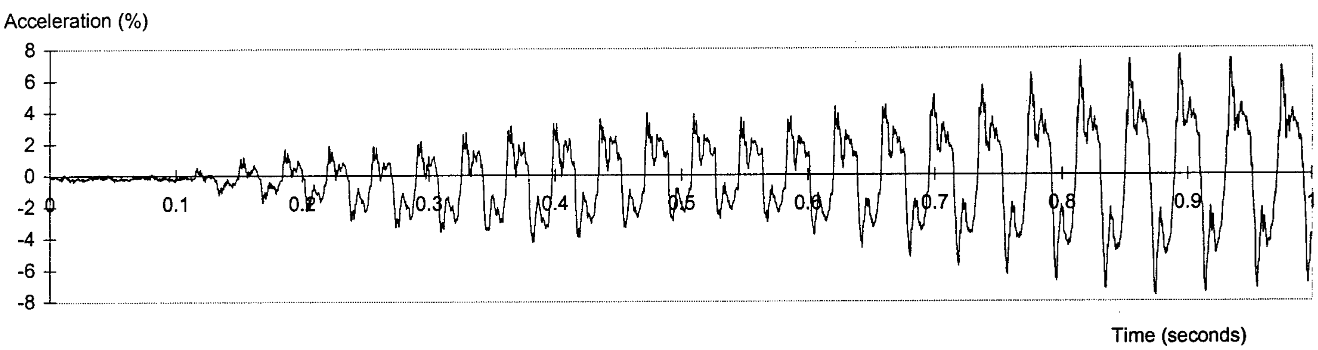
Acc 7314 Outside of ESB (ring 2) horizontal



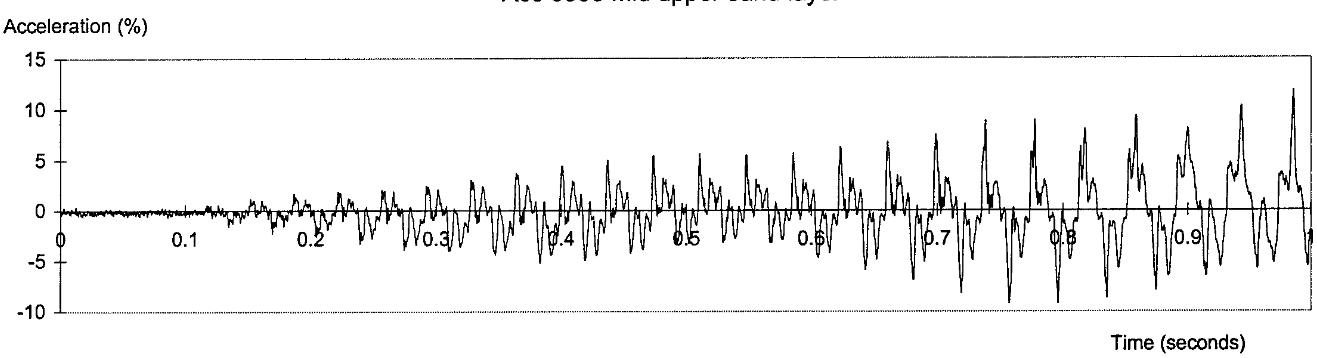
Acc 1925 Outside ESB (ring 5) horizontal (calibration estimated)



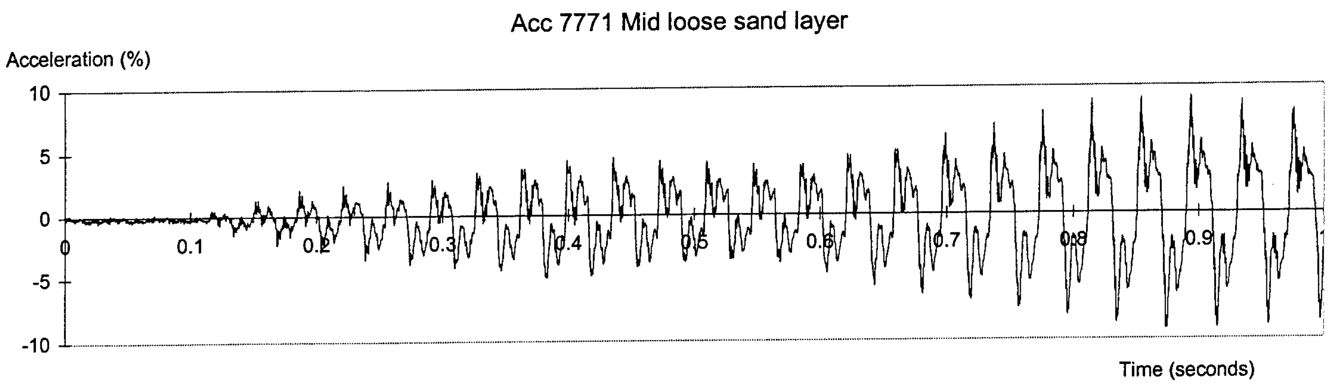
Acc 7318 Bottom of loose sand layer

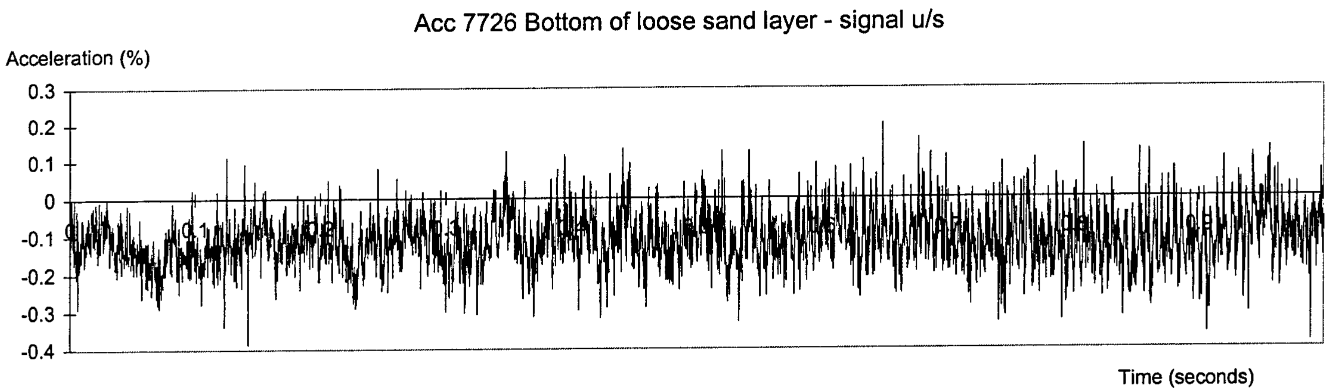


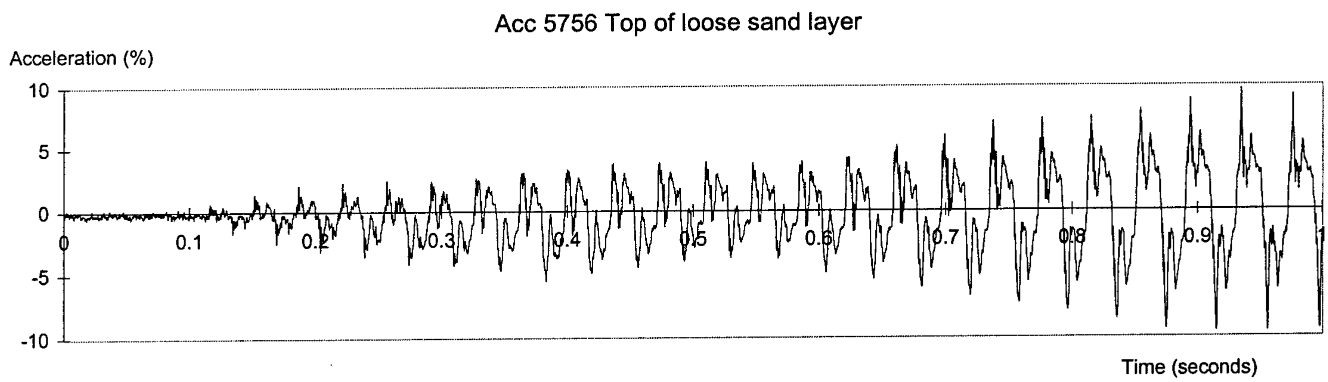
Acc 6835 Mid upper sand layer

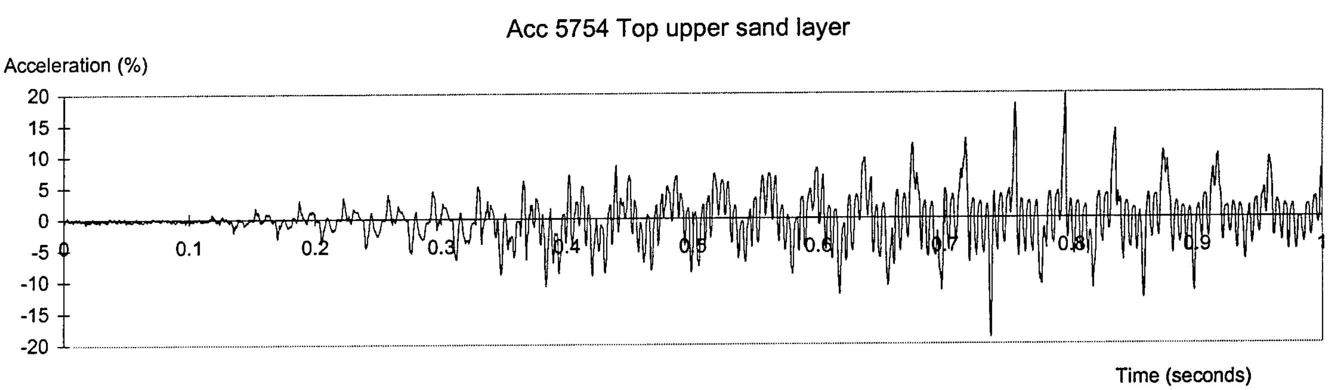


eqr1_1 Figure 1a/1/1 Model 1a, Earthquake 1

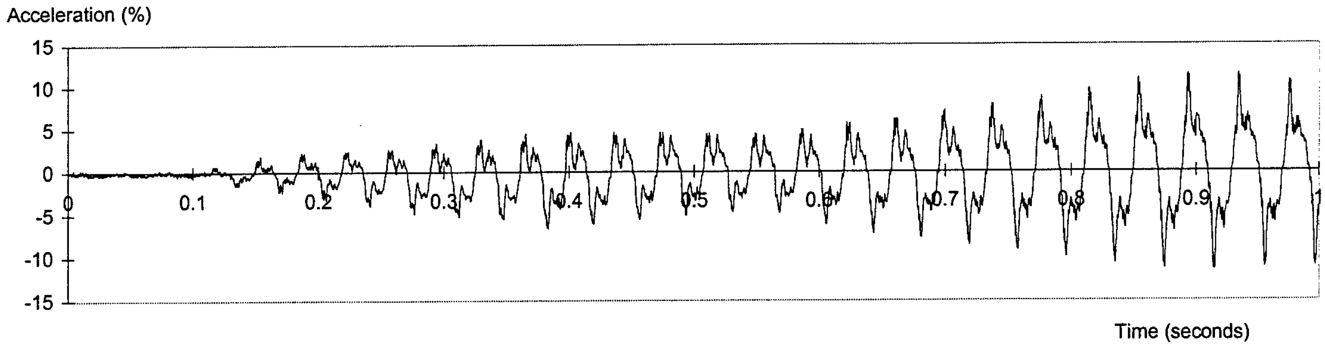

Acc 7771 Mid loose sand layer
Acceleration (%)
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time (seconds)


Acc 7726 Bottom of loose sand layer - signal u/s
Acceleration (%)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Time (seconds)

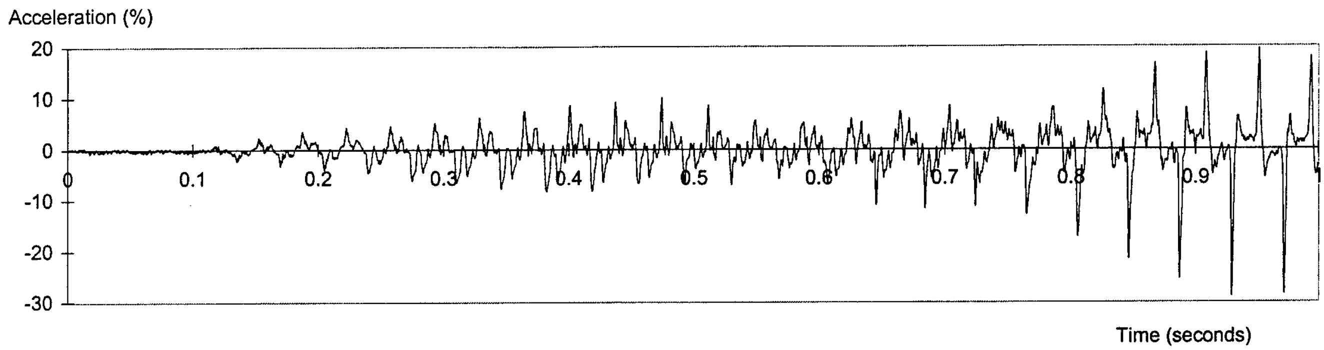

Acc 5756 Top of loose sand layer
Acceleration (%)
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)


Acc 5754 Top upper sand layer
Acceleration (%)
20
15
10
5
0
-5
-10
-15
-20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)

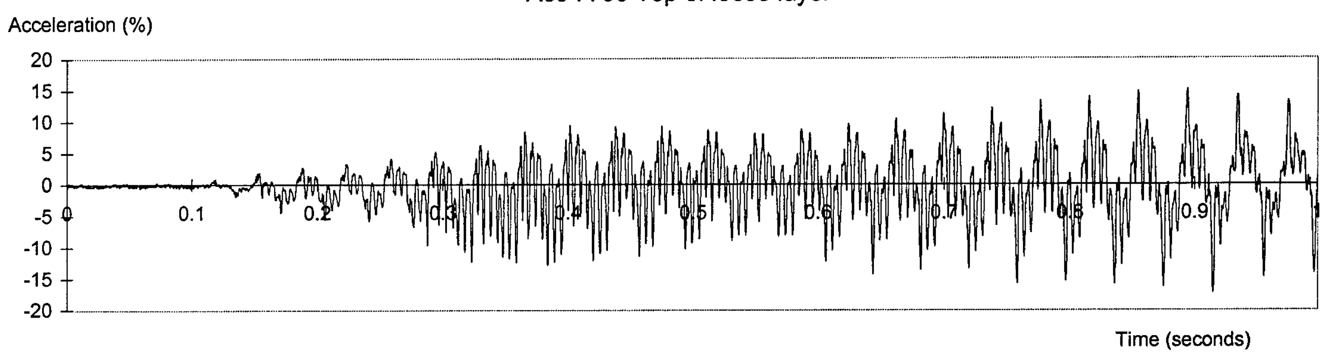
Acc 7828 Mid loose sand layer



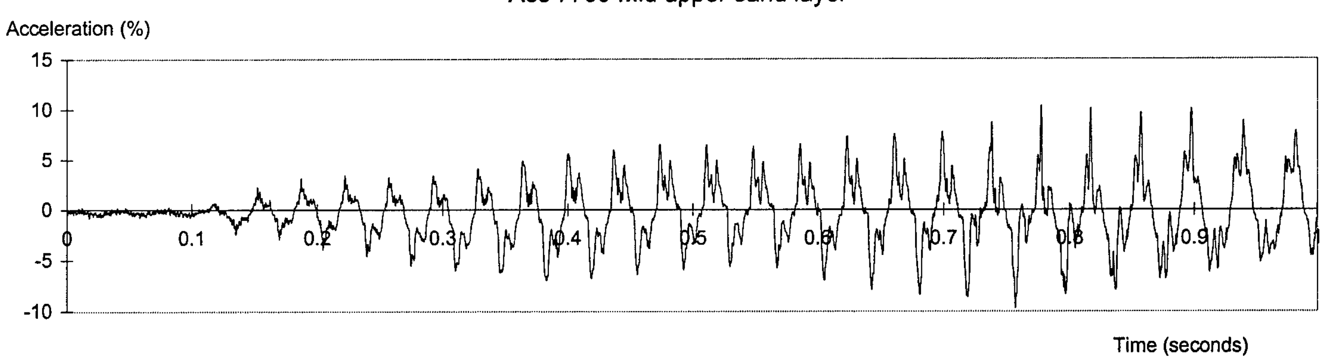
Acc 3457 Top of upper sand layer



Acc 7706 Top of loose layer

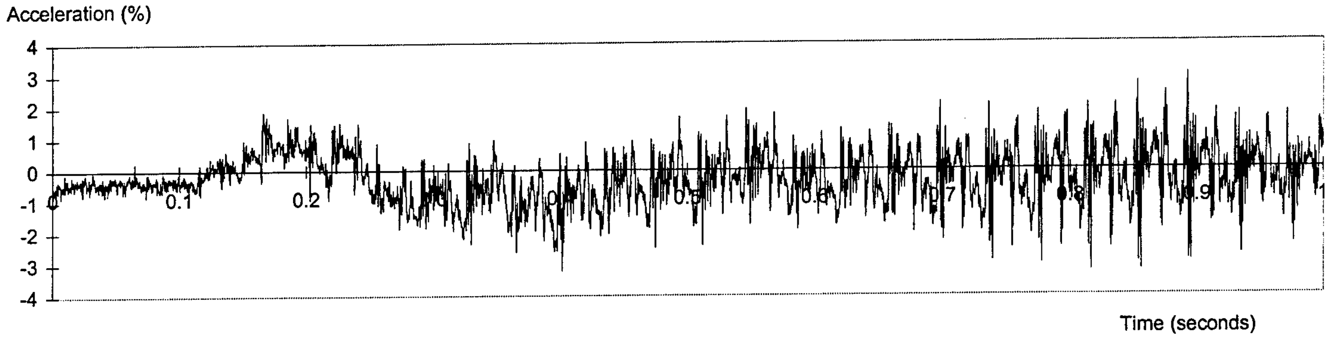


Acc 7709 Mid upper sand layer

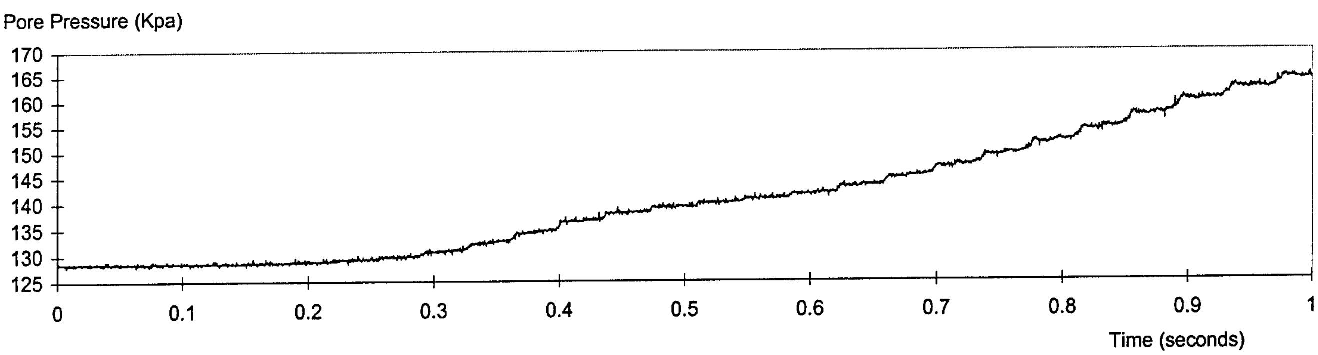


eqr1_1 Figure 1a/1/3 Model 1a, Earthquake 1

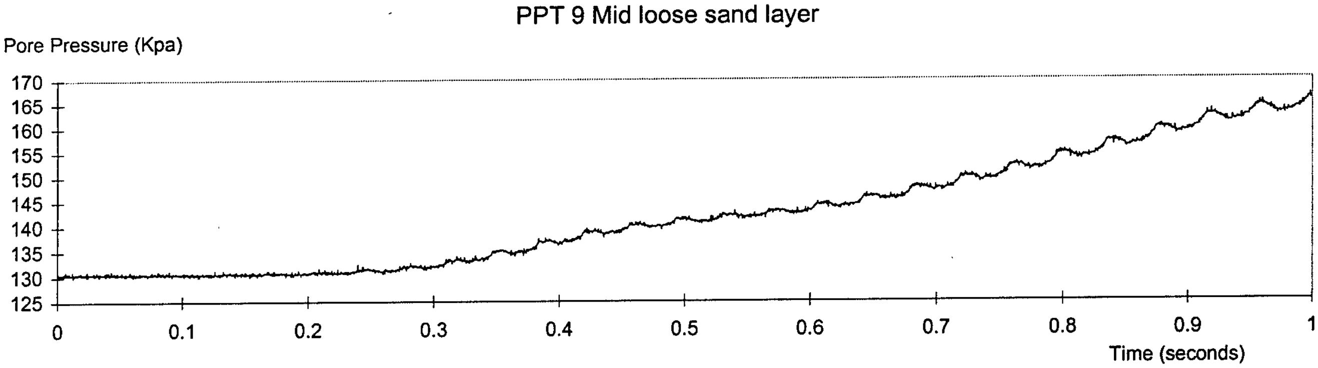
Acc 7319 Outside of ESB container (base plate) vertical



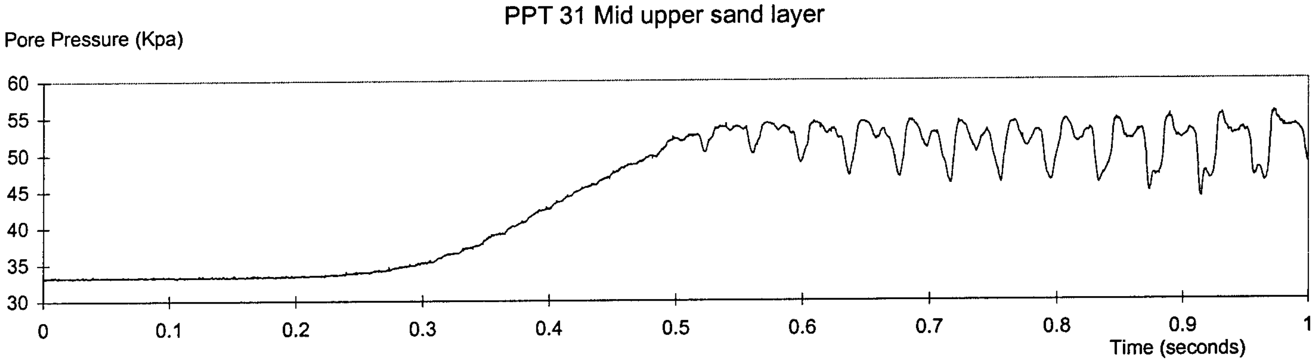
PPT 10 Mid loose sand layer



PPT 9 Mid loose sand layer



PPT 31 Mid upper sand layer

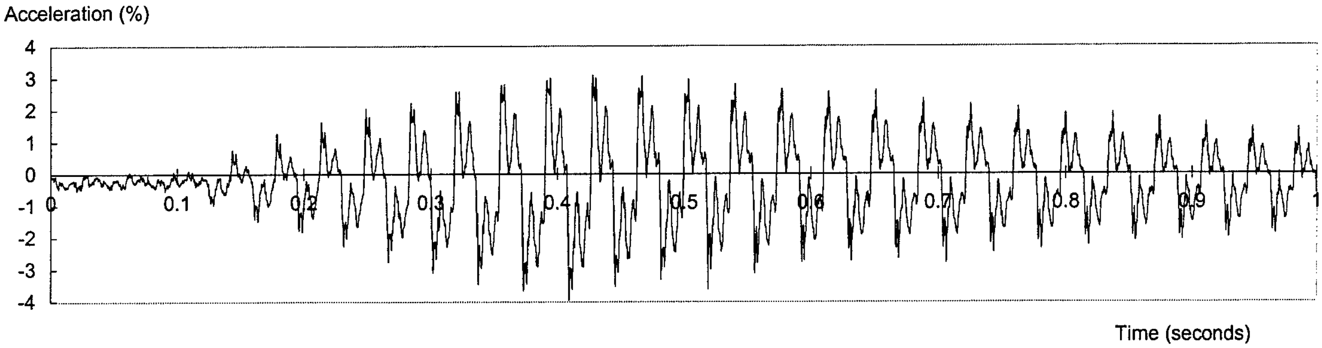


eqr1_1

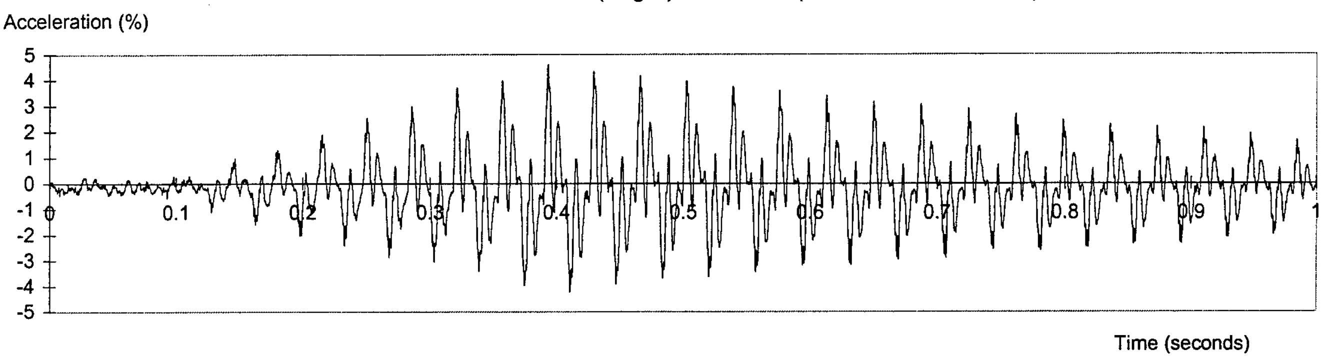
Figure 1a/1/4

Model 1a, Earthquake 1

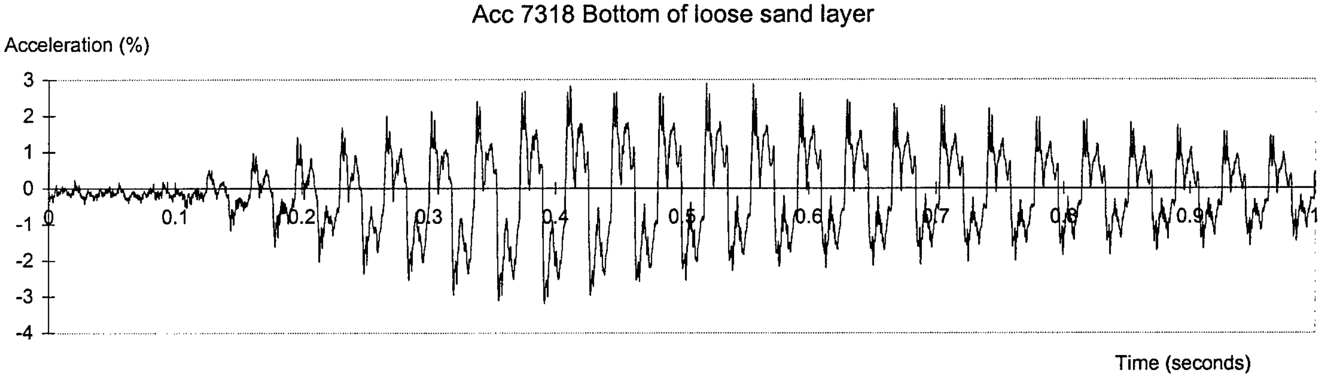
Acc 7314 Outside of ESB (ring 2) horizontal



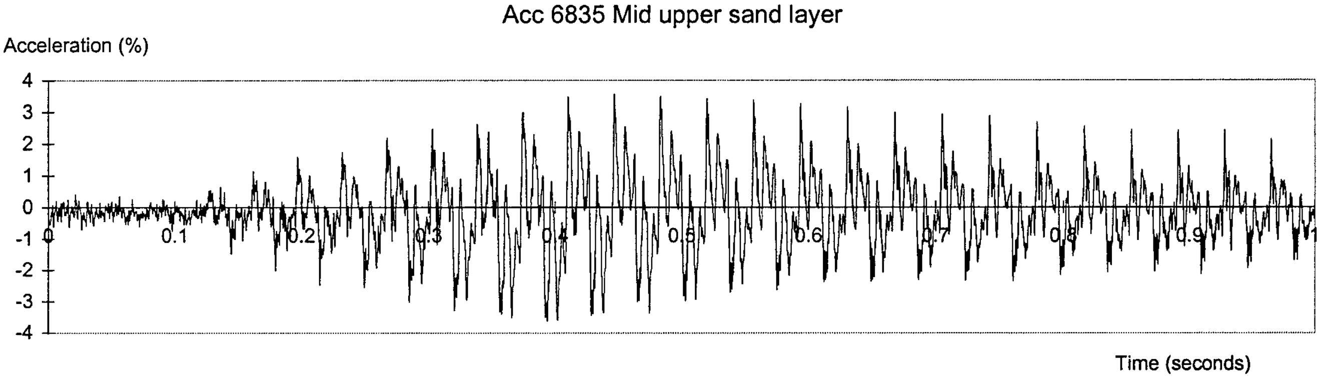
Acc 1925 Outside of ESB (ring 5) horizontal (calibration estimated)

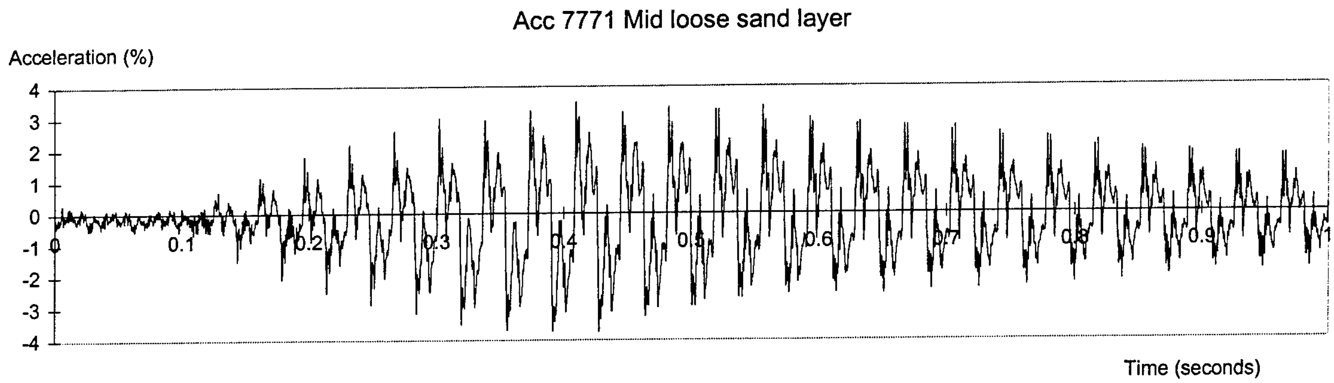


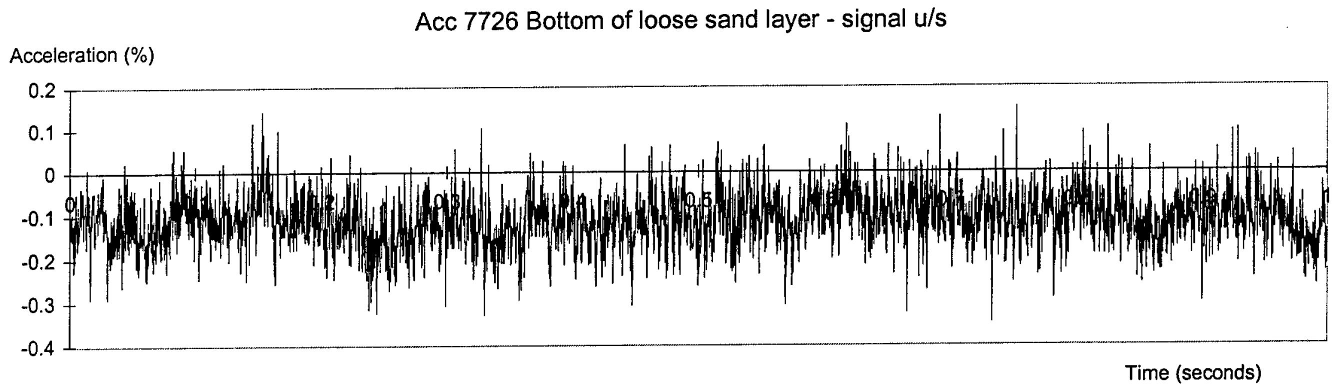
Acc 7318 Bottom of loose sand layer

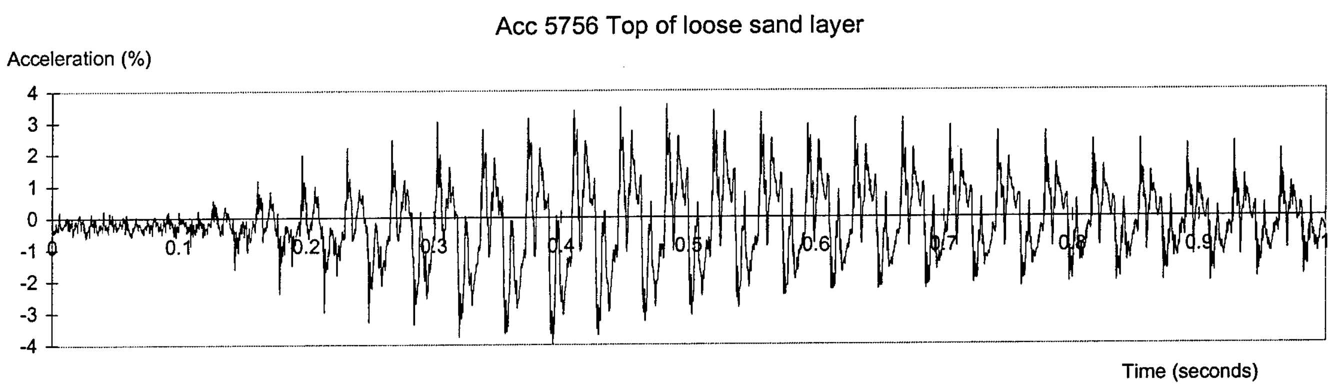


Acc 6835 Mid upper sand layer




Acc 7771 Mid loose sand layer
Acceleration (%)
4
3
2
1
0
-1
-2
-3
-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)


Acc 7726 Bottom of loose sand layer - signal u/s
Acceleration (%)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Time (seconds)


Acc 5756 Top of loose sand layer
Acceleration (%)
4
3
2
1
0
-1
-2
-3
-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)

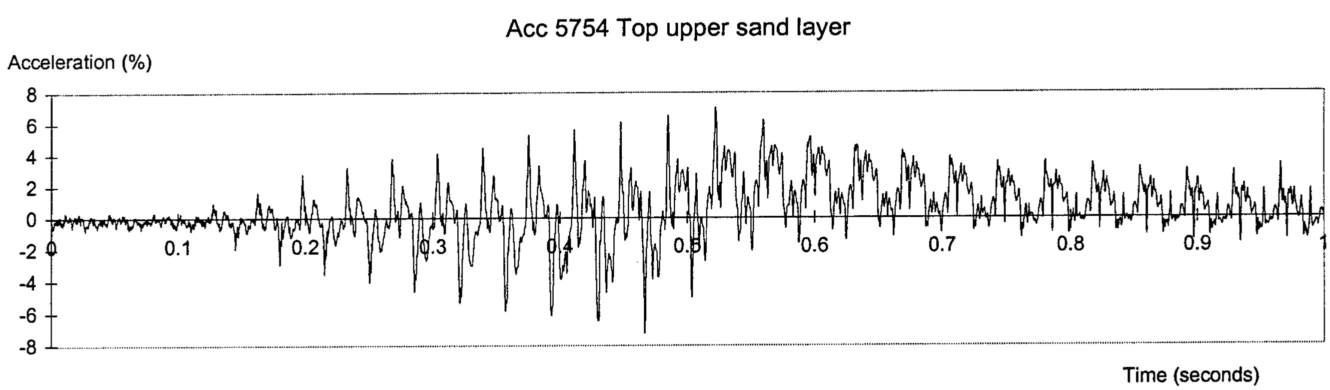
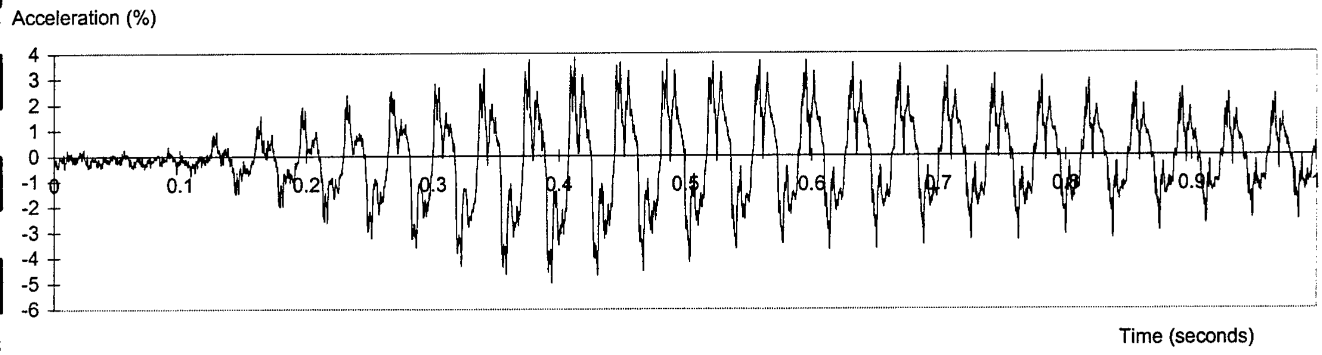
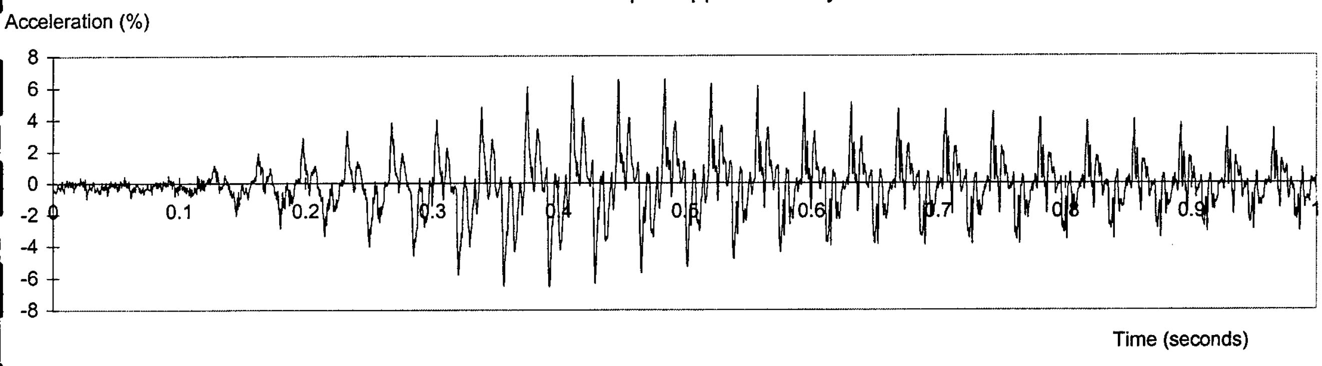

Acc 5754 Top upper sand layer
Acceleration (%)
8
6
4
2
0
-2
-4
-6
-8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)

Figure 1a/2/2

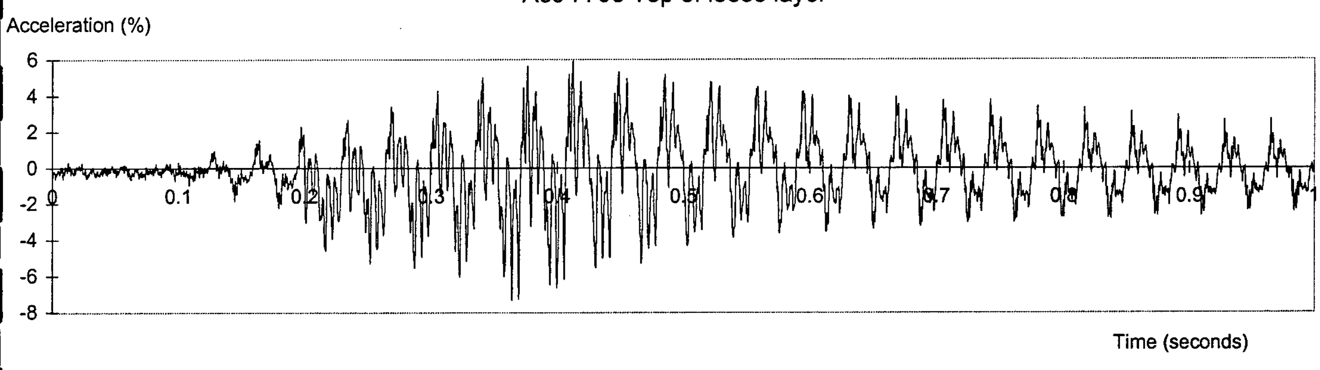
Acc 7828 Mid loose sand layer



Acc 3457 Top of upper sand layer



Acc 7706 Top of loose layer



Acc 7709 Mid upper sand layer

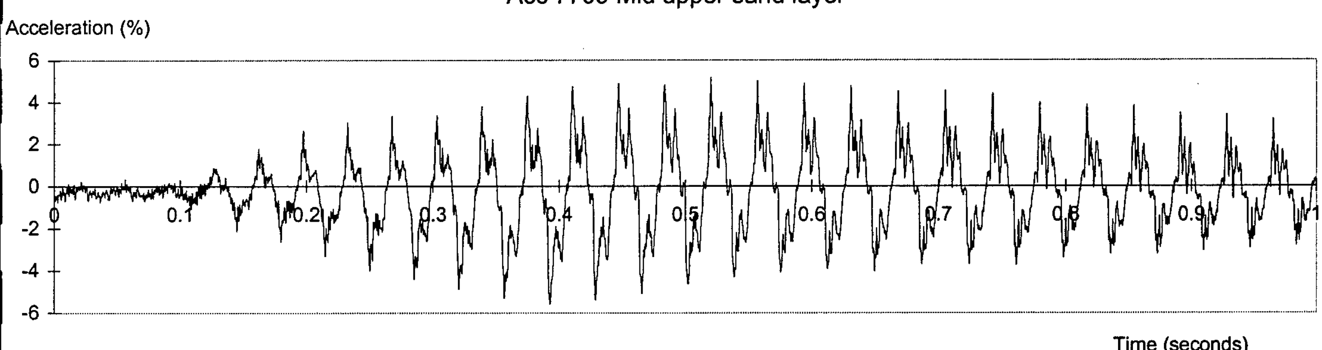
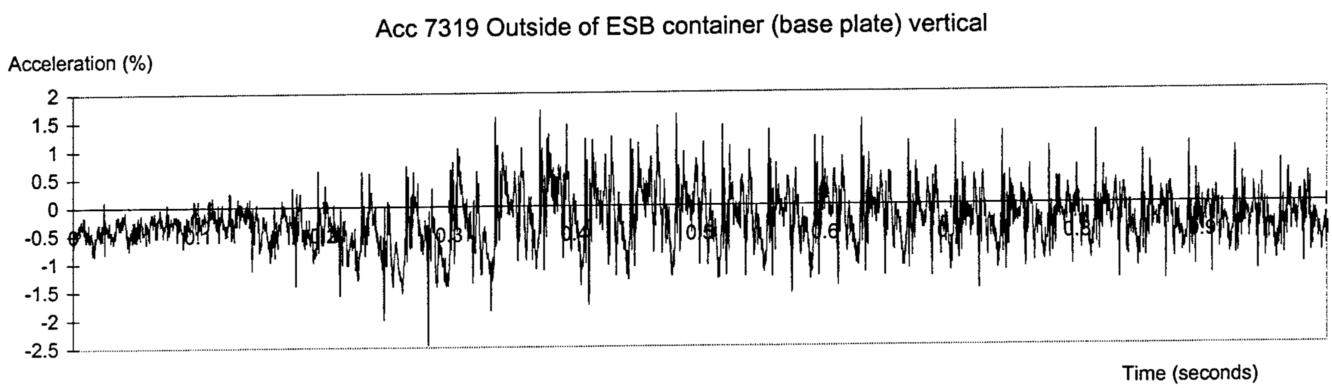
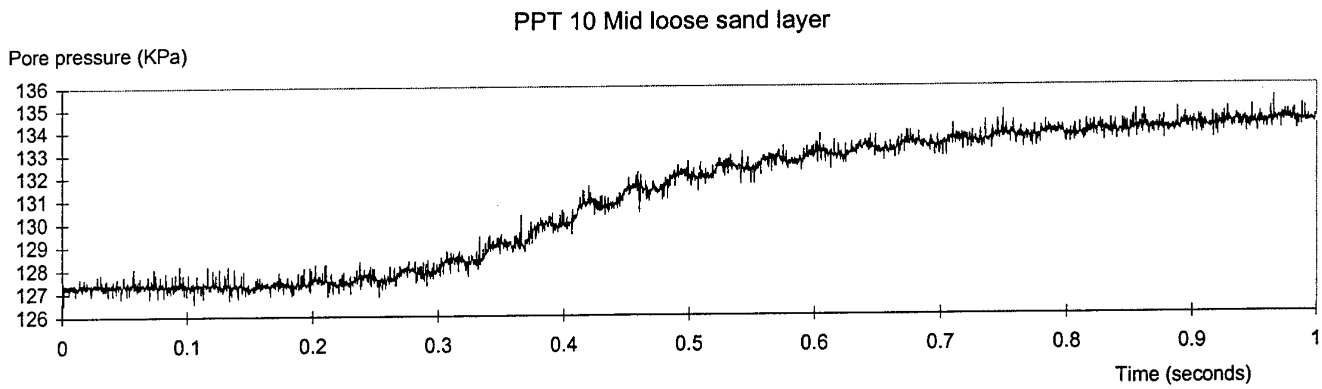
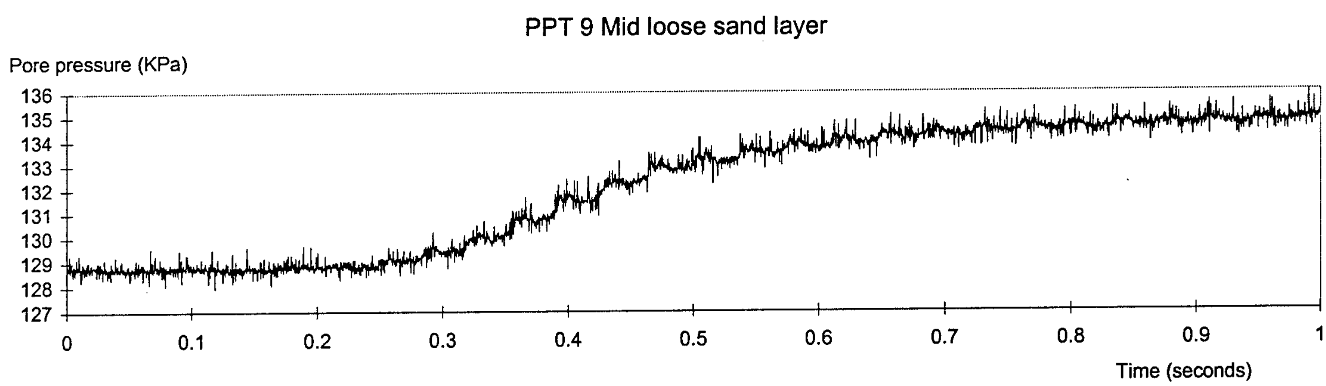
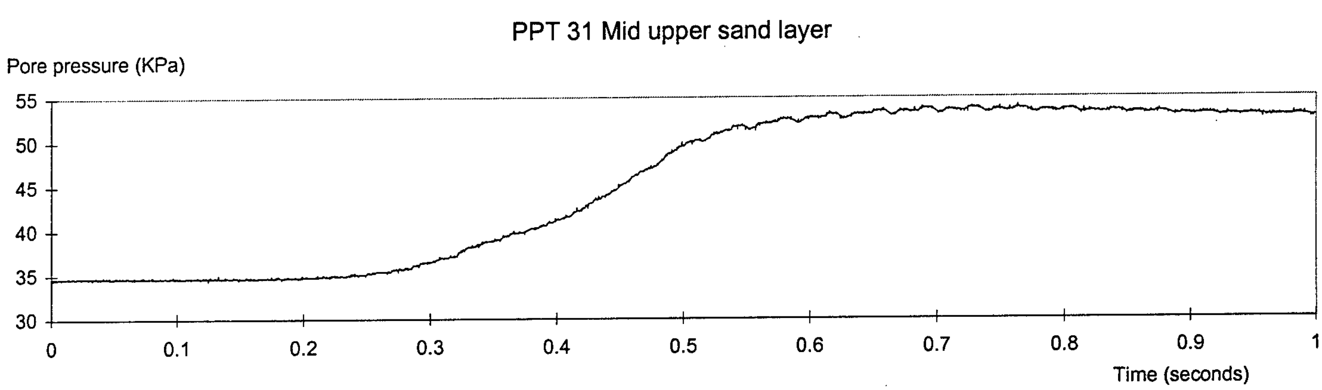


Figure 1a/2/3


Acc 7319 Outside of ESB container (base plate) vertical
Acceleration (%)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Time (seconds)


PPT 10 Mid loose sand layer
Pore pressure (KPa)
136
135
134
133
132
131
130
129
128
127
126
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)


PPT 9 Mid loose sand layer
Pore pressure (KPa)
136
135
134
133
132
131
130
129
128
127
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)


PPT 31 Mid upper sand layer
Pore pressure (KPa)
55
50
45
40
35
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (seconds)

CALIBRATION OF ACCELEROMETERS

The attached worksheet presents the results of calibrations of accelerometers carried out at WES on 5, 6 December 1997.

The accelerometers are tested on a shake table at a range of frequencies and amplitudes. The mean calibration is computed, together with the standard deviation for each device. The channel number refers to the junction box.

Accelerometer calibration 5, 6 December 1997
Miller

ACC/ch	g	30Hz	40Hz	80Hz	mean calib/std dev	notes
7319	1	124.79	123.65	122.1	123.26 mV/g	
ch2	5	124.52	123.44	121.86	1.10	
05-Dec-97	10	124.42	123.34	121.91		
	20	124.04	123.16	121.85		
7828	1	124.39	124.56	123.46	124.21 mV/g	
ch3	5	124.54	124.5	123.41	0.61	
05-Dec-97	10	124.82	124.48	123.43		
	20	125.09	124.41	123.41		
7709	1	122.93	121.45	120.33	121.20 mV/g	
ch4	5	122.18	121.05	120.18	0.87	
05-Dec-97	1	121.73	121.1	120.13		
	20	121.79	121.19	120.39		
7318	1	112.19	112.48	111.62	111.88 mV/g	
ch5	5	112.25	111.94	111.58	0.30	
06-Dec-97	10	111.9	111.81	111.58		
	20	111.85	111.83	111.47		
7706	1	138.15	136.86	134.86	136.39 mV/g	
ch1	5	137.75	136.69	134.86	1.18	
06-Dec-97	10	137.22	136.62	134.87		
	20	137.03	136.72	135.04		
7771	1	135.77	134.85	134.22	134.94 mV/g	
ch7	5	135.82	135.02	134.06	0.65	
06-Dec-97	10	135.61	135.1	134.11		
	20	135.38	135.11	134.27		
7726	1	138.49	137.44	136.44	137.15 mV/g	
ch8	5	137.77	137.36	136.17	0.76	
06-Dec-97	10	137.71	137.27	136.18		
	20	137.62	137.17	136.13		
7314	1	113.83	113.46	112.88	113.30 mV/g	
ch10	5	113.67	113.31	112.8	0.38	
06-Dec-97	10	113.66	113.33	112.81		
	20	113.63	113.42	112.79		
6835	1	129.85	129.5	128.72	129.10 mV/g	
ch11	5	129.73	129.26	128.58	0.56	
06-Dec-97	10	129.68	129.25	128.65		
	20	128.09	129.24	128.62		
5754	1	116.3	115.52	114.63	115.28 mV/g	low output, changed
ch12	5	116.01	115.53	114.38	0.71	cable
06-Dec-97	10	115.78	115.72	114.32		
	20	115.52	115.47	114.23		

ACC/ch	g	30Hz	40Hz	80Hz	mean calib/std dev	notes
5756	1	112.02	111.86	111.23	111.70 mV/g	
ch13	5	112.01	112.01	111.02	0.47	
06-Dec-97	10	112.07	112.09	111.04		
	20	111.98	112.02	110.99		
3457	1	113.05	112.12	112.22	112.40 mV/g	
ch14	5	113.12	112.19	112.26	0.35	
06-Dec-97	10	112.5	112.25	112.31		
	20	111.97	112.38	112.45		

07-Dec-97
J Box check out
loaded with 12 powered
up accelerometers

ch	status
1	OK
2	OK
3	OK
4	OK
5	OK
6	no output
7	OK
8	OK
9	OK
10	OK
11	OK
12	OK
13	OK
14	OK
15	OK
16	OK
17	OK
18	OK
19	OK
20	OK
21	OK
22	OK
23	OK
24	OK

APPENDIX D

ESB CONTAINER DESIGN

Calculations of lateral shear stiffness

ESB CONTAINER DESIGN

The attached worksheet present a series of calculations concerning the design of the ESB container for experiments at 50g, with the container filled with saturated sand at any given void ratio and for a depth of water table variable down to mid-depth. The calculation could readily be used to compute the stiffness at any other g level.

The calculation aims simply to compute the shear modulus appropriate to a sand of specified void ratio under a given mean effective confining pressure computed at mid-depth. This low strain modulus is then degraded by a range of excess pore pressures, which are chosen as a percentage of the effective vertical stress. Strain degradation is based on the standard curves reproduced in the Handbook on liquefaction remediation of reclaimed land (PHRI).

The shear modulus is then obtained as a function of strain and excess pore pressure. This is compared with the strain calculated by assuming a uniform shear modulus for the entire container and computing the base shear as a function of the lateral acceleration field (treated pseudo-statically).

A combination of strain level and shear modulus is chosen as a compatible set, and the excess pore pressure and lateral acceleration field deduced. Finally the displacement of the chamber is calculated and the design rubber stiffness deduced.

ESB container design

This calculation is based on earthq04.xls and computes the shear modulus for the ESB container filled with saturated sand at 50g, including the effects of strain softening and excess pore pressure. The calculation then computes the base shear (pseudo-static) and the approximate deflection of the ESB chamber under a range of lateral accelerations. A base plate and two porous plates are assumed.

Nevada sand	
Maximum void ratio	0.756
Minimum void ratio	0.516
Specific gravity	2.64
Sand Relative density	65%
Void ratio	0.6
Dry weight	16.2 KN/m^3
Bouyant weight	10.1 KN/m^3
Saturated weight	19.9 KN/m^3
Nevada sand D_{50} (approx)	0.18 mm
Nevada sand D_{10} (approx)	0.11 mm

Nominal g at 6 m 50 gravities

Sand Layer centroid	5.641 m
Base plate plus two 1/8" porous plates	19 mm total thickness
Base plates centroid	5.9405 m

Sand layer	
Depth to wt	0 mm
Depth below wt	580 mm
Equivalent depth (approximate)	29.0 m
Depth to middle of layer	290 mm
Check wt above middle of layer	OK
Check overall depth is less than 600	OK

Excess pore pressure	0%	20%	40%	60%	
Effective vertical stress, σ_v' at mid-depth	137.1	109.7	82.2	54.8	KPa
Effective vertical stress, σ_v' at base	274.2	219.3	164.5	109.7	KPa
or σ_v'	2.56	2.04	1.53	1.02	tsf
Ko	0.5	0.5	0.5	0.5	
σ_m' (mid-depth)	91.4	73.1	54.8	36.6	KPa
σ_m' (base)	182.8	146.2	109.7	73.1	KPa
Go (round particles) at mid-depth	102088	91310	79077	64566	KPa
Go (angular particles) at mid-depth	109948	98340	85165	69537	KPa
Go (round particles) at base of layer	144374	129132	111832	91310	KPa
Go (angular particles) at base of layer	155490	139074	120442	98340	KPa

ESB design, calculation contd.

Data from Table 4.10 of shear modulus for sands, angular particles, ref 1

Equivalent uniform G calculated at mid-depth (assuming angular particles)

Strain amplitude	A	n	Strain %	0%	20%	40%	60% excess pp
10^{-6}	1	0	0.0001	109948	98340	85165	69537
10^{-5}	0.93	0.01	0.001	102890	91823	79292	64480
5×10^{-5}	0.83	0.03	0.005	92977	82607	70925	57210
10^{-4}	0.75	0.05	0.01	85068	75243	64232	51393
2.5×10^{-4}	0.56	0.1	0.025	65526	57315	48229	37814
5×10^{-4}	0.43	0.16	0.05	52230	45077	37282	28528
10^{-3}	0.3	0.22	0.1	37826	32212	26186	19556
2.5×10^{-3}	0.15	0.3	0.25	19879	16629	13210	9551

Data from Table 4.12 for damping factor h for sands, ref 1

Strain amplitude	$h_{average}$	$h_{maximum}$	$h_{minimum}$	Strain amplitude (%)	Average damping (%)
10^{-6}	0.026	0.04	0.016	0.0001	2.6
10^{-5}	0.03	0.04	0.018	0.001	3.0
5×10^{-5}	0.033	0.042	0.02	0.005	3.3
10^{-4}	0.037	0.048	0.026	0.01	3.7
2.5×10^{-4}	0.055	0.068	0.04	0.025	5.5
5×10^{-4}	0.08	0.098	0.06	0.05	8.0
10^{-3}	0.12	0.145	0.092	0.1	12.0
2.5×10^{-3}	0.174	0.2	0.148	0.25	17.4

Ref 1: Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997, p64.

Average strain and box displacement

Width of ESB	315	mm
Length of ESB	800	mm
Area of soil	0.252	m^2
Area of rubber per layer	0.0675	m^2
Mass of soil	295.974	kg
Mass of ESB container (above base plate)	117.47	kg
Weight of soil and ESB above mid-depth	101.39714	KN (approximately)

Average Strain

Earthquake amplitude		2%	6%	8%	16%	32%	
Average mid-depth shear stress		6.3472389	19.041717	25.388955	50.777911	101.5558	KN/m^2
Average shear modulus (MPa)	10	**6.35E-04**	1.90E-03	**2.54E-03**	5.08E-03	1.02E-02	strain
	12	5.29E-04	1.59E-03	2.12E-03	4.23E-03	8.46E-03	strain
	14	4.53E-04	1.36E-03	1.81E-03	3.63E-03	7.25E-03	strain
	16	3.97E-04	1.19E-03	1.59E-03	3.17E-03	6.35E-03	strain
	18	3.53E-04	1.06E-03	1.41E-03	2.82E-03	5.64E-03	strain
	20	3.17E-04	**9.52E-04**	1.27E-03	**2.54E-03**	5.08E-03	strain
	25	2.54E-04	7.62E-04	1.02E-03	2.03E-03	4.06E-03	strain
	30	2.12E-04	6.35E-04	8.46E-04	1.69E-03	3.39E-03	strain
	40	1.59E-04	4.76E-04	6.35E-04	1.27E-03	2.54E-03	strain
	60	1.06E-04	3.17E-04	4.23E-04	8.46E-04	1.69E-03	strain
	80	7.93E-05	2.38E-04	3.17E-04	6.35E-04	1.27E-03	strain
	110	5.77E-05	1.73E-04	2.31E-04	4.62E-04	9.23E-04	strain

ESB design, calculation contd.

Shear stiffness, MPa	G_{av}	G_{rubber}	2%	6%	8%	16%	32%

Average displacement at top of ESB container	10	0.67	0.3808343	1.14	1.52	3.05	6.09 mm
	12	0.80	0.3173619	0.95	1.27	2.54	5.08 mm
	14	0.93	0.2720245	0.82	1.09	2.18	4.35 mm
	16	1.07	0.2380215	0.71	0.95	1.90	3.81 mm
	18	1.20	0.2115746	0.63	0.85	1.69	3.39 mm
	20	1.33	0.1904172	0.57	0.76	1.52	3.05 mm
	25	1.67	0.1523337	0.46	0.61	1.22	2.44 mm
	30	2.00	0.1269448	0.38	0.51	1.02	2.03 mm
	40	2.67	0.0952086	0.29	0.38	0.76	1.52 mm
	60	4.00	0.0634724	0.19	0.25	0.51	1.02 mm
	80	5.33	0.0476043	0.14	0.19	0.38	0.76 mm
	110	7.33	0.0346213	0.10	0.14	0.28	0.55 mm

ESB DESIGN
MODELS 1 & 2, SERIES 1

The attached worksheet present a series of calculations concerning the design of the ESB container models for Models 1 and 2 of Series 1 under the EQEN test series. An outline of the models is presented in the word document entitled Earthquake Model Test Plan.

The calculation aims simply to compute the shear modulus appropriate to a Nevada sand of specified void ratio under a given mean effective confining pressure. This low strain modulus is then degraded by a range of excess pore pressures, which are chosen as a percentage of the effective vertical stress. Strain degradation is based on the standard curves reproduced in the Handbook on liquefaction remediation of reclaimed land (PHRI).

The shear modulus is then obtained as a function of strain and excess pore pressure. This is compared with the strain calculated by assuming a uniform shear modulus for the entire container and computing the shear as a function of the lateral acceleration field (treated pseudo-statically). This is based on a crude assumption that at around mid-depth the mass of half the soil and half the container (above the base plate) are subject to a D'Alembert body force in a lateral direction. Clearly this is not precise, nor is it strictly at the correct elevation in the ESB container (mid depth in the loose layer is around 100 mm above the base of the container) but for the purposes of this calculation this is considered to give a solution of the right order of magnitude.

A combination of strain level and shear modulus is chosen as a compatible set, and the excess pore pressure and lateral acceleration field deduced. Finally the displacement of the chamber is calculated and the design rubber stiffness deduced.

ESB Design, Models 1 & 2 (Nevada sand)

This calculation is based on earthq04.xls and solves for the design stiffness of the ESB container for Models 1 and 2 of Series 1. A base plate and two porous plates are assumed.

Nevada sand (density and depth to achieve mean effective confining pressure)

Maximum void ratio	0.756	
Minimum void ratio	0.516	
Specific gravity	2.64	
Sand Relative density	35%	
Void ratio	0.673	fixed, as has influence on Go
Dry weight	15.5	KN/m^3
Bouyant weight	9.6	KN/m^3
Saturated weight	19.4	KN/m^3
Nevada sand D_{50} (approx)	0.18	mm
Nevada sand D_{10} (approx)	0.11	mm

Nominal g at 6 m 50 gravities

Sand Layer centroid	5.697	m
Base plate plus two 1/8" porous plates	19	mm total thickness
Base plates centroid	5.9405	m

Sand layer

Depth to wt	0	mm
Depth below wt	468	mm
Equivalent depth (approximate)	23.4	m
Depth to middle of layer	234	mm
Check wt above middle of layer	OK	
Check overall depth is less than 600	OK	

Excess pore pressure	0%	20%	40%	60%	
Effective vertical stress, σ_v' at mid-depth	106.8	85.5	64.1	42.7	KPa
Effective vertical stress, σ_v' at base	213.7	170.9	128.2	85.5	KPa
or σ_v'	1.99	1.59	1.20	0.80	tsf
Ko	0.5	0.5	0.5	0.5	
σ_m' (mid-depth) target value see calc. earthq04.xls	**71.2**	57.0	42.7	28.5	KPa
σ_m' (base)	142.4	114.0	85.5	57.0	KPa
Go (round particles) at mid-depth	78.36	70.09	60.70	49.56	MPa
Go (angular particles) at mid-depth	**87.20**	78.00	67.55	55.15	MPa
Go (round particles) at base of layer	110.82	99.12	85.84	70.09	MPa
Go (angular particles) at base of layer	123.33	110.31	95.53	78.00	MPa

ESB design, calculation contd.

Data from Table 4.10 of shear modulus for sands, angular particles, ref 1

Equivalent uniform G calculated at mid-depth (assuming angular particles)

Strain amplitude	A	n	Strain %	0%	20%	40%	60% excess pp
10^{-6}	1	0	0.0001	**87.20**	78.00	67.55	55.15 MPa
10^{-5}	0.93	0.01	0.001	81.40	72.65	62.73	51.01 MPa
5×10^{-5}	0.83	0.03	0.005	73.19	65.03	55.83	45.04 MPa
10^{-4}	0.75	0.05	0.01	66.64	58.94	50.31	40.26 MPa
2.5×10^{-4}	0.56	0.1	0.025	50.69	44.34	37.31	29.25 MPa
5×10^{-4}	0.43	0.16	0.05	**39.81**	34.35	28.41	21.74 MPa
10^{-3}	0.3	0.22	0.1	28.40	**24.19**	19.66	**14.68** MPa
2.5×10^{-3}	0.15	0.3	0.25	14.63	12.24	**9.72**	7.03 MPa

Data from Table 4.12 for damping factor h for sands, ref 1

Strain amplitude	$h_{average}$	$h_{maximum}$	$h_{minimum}$	Strain amplitude (%)	Average damping (%)
10^{-6}	0.026	0.04	0.016	0.0001	2.6
10^{-5}	0.03	0.04	0.018	0.001	3.0
5×10^{-5}	0.033	0.042	0.02	0.005	3.3
10^{-4}	0.037	0.048	0.026	0.01	3.7
2.5×10^{-4}	0.055	0.068	0.04	0.025	5.5
5×10^{-4}	0.08	0.098	0.06	0.05	8.0
10^{-3}	0.12	0.145	0.092	0.1	12.0
2.5×10^{-3}	0.174	0.2	0.148	0.25	17.4

Ref 1: Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997, p64.

Average strain and box displacement

Width of ESB	315	mm
Length of ESB	800	mm
Area of soil	0.252	m^2
Area of rubber per layer	0.0675	m^2
Mass of soil	233.54571	kg
Mass of ESB container (above base plate)	117.47	kg
Weight of soil and ESB above mid-depth	86.086602	KN (approximately - based on half soil and ESB)

Average Strain

Earthquake amplitude		0%	5%	10%	30%	40%	
Average base shear stress		0	13.472082	26.944163	80.83249	107.7767	KN/m^2
Average shear modulus (MPa)	5	0.00E+00	2.69E-03	5.39E-03	1.62E-02	2.16E-02	strain
	10	0.00E+00	1.35E-03	**2.69E-03**	8.08E-03	1.08E-02	strain
	15	0.00E+00	**8.98E-04**	1.80E-03	5.39E-03	7.19E-03	strain
	20	0.00E+00	6.74E-04	1.35E-03	4.04E-03	5.39E-03	strain
	25	0.00E+00	5.39E-04	**1.08E-03**	3.23E-03	4.31E-03	strain
	30	0.00E+00	4.49E-04	8.98E-04	2.69E-03	3.59E-03	strain
	35	0.00E+00	3.85E-04	7.70E-04	2.31E-03	3.08E-03	strain
	40	0.00E+00	3.37E-04	**6.74E-04**	2.02E-03	2.69E-03	strain
	45	0.00E+00	2.99E-04	5.99E-04	1.80E-03	2.40E-03	strain
	50	0.00E+00	2.69E-04	5.39E-04	1.62E-03	2.16E-03	strain
	55	0.00E+00	2.45E-04	4.90E-04	1.47E-03	1.96E-03	strain
	60	0.00E+00	2.25E-04	4.49E-04	1.35E-03	1.80E-03	strain

ESB design, calculation contd.

Shear stiffness, MPa	G_{av}	G_{rubber}	0%	5%	10%	30%	40%	
Average displacement	5	0.33	0	1.62	3.23	9.70	12.93	mm
at top of ESB container	10	0.67	0	0.81	1.62	4.85	6.47	mm
	15	1.00	0	0.54	1.08	3.23	4.31	mm
	20	1.33	0	0.40	0.81	2.42	3.23	mm
	25	1.67	0	0.32	0.65	1.94	2.59	mm
	30	2.00	0	0.27	0.54	1.62	2.16	mm
	35	2.33	0	0.23	0.46	1.39	1.85	mm
	40	2.67	0	0.20	0.40	1.21	1.62	mm
	45	3.00	0	0.18	0.36	1.08	1.44	mm
	50	3.33	0	0.16	0.32	0.97	1.29	mm
	55	3.67	0	0.15	0.29	0.88	1.18	mm
	60	4.00	0	0.13	0.27	0.81	1.08	mm

Conclusion

Several solutions exists at 0, 20, 40 and 60% excess pore pressure, with strains varying from 5×10^{-4} to 2.5×10^{-3} and earthquake strengths varying upto 10%.
The average shear modulus of the ESB container could range from 10 to 40 MPa.
Deflection at the top of the ESB container vary from 0.4 to 1.6 mm accordingly.

ESB DESIGN
MODEL 3, SERIES 1

The attached worksheet present a series of calculations concerning the design of the ESB container models for Model 3 of Series 1 under the EQEN test series. An outline of the models is presented in the word document entitled Earthquake Model Test Plan.

The calculation aims simply to compute the shear modulus appropriate to a Nevada sand of specified void ratio under a given mean effective confining pressure. This low strain modulus is then degraded by a range of excess pore pressures, which are chosen as a percentage of the effective vertical stress. Strain degradation is based on the standard curves reproduced in the Handbook on liquefaction remediation of reclaimed land (PHRI).

The shear modulus is then obtained as a function of strain and excess pore pressure. This is compared with the strain calculated by assuming a uniform shear modulus for the entire container and computing the shear as a function of the lateral acceleration field (treated pseudo-statically). This is based on a crude assumption that at around mid-depth the mass of half the soil and half the container (above the base plate) are subject to a D'Alembert body force in a lateral direction. Clearly this is not precise, nor is it strictly at the correct elevation in the ESB container (mid depth in the loose layer is around 100 mm above the base of the container) but for the purposes of this calculation this is considered to give a solution of the right order of magnitude.

A combination of strain level and shear modulus is chosen as a compatible set, and the excess pore pressure and lateral acceleration field deduced. Finally the displacement of the chamber is calculated and the design rubber stiffness deduced.

ESB Design, Model 3 (Nevada sand)

This calculation is based on earthq04.xls and solves for the design stiffness of the ESB container for Models 1 and 2 of Series 1. A base plate and two porous plates are assumed.

Nevada sand (density and depth to achieve mean effective confining pressure)

Maximum void ratio	0.756	
Minimum void ratio	0.516	
Specific gravity	2.64	
Sand Relative density	35%	
Void ratio	0.673	fixed, as has influence on Go
Dry weight	15.5	KN/m^3
Bouyant weight	9.6	KN/m^3
Saturated weight	19.4	KN/m^3
Nevada sand D_{50} (approx)	0.18	mm
Nevada sand D_{10} (approx)	0.11	mm

Nominal g at 6 m 50 gravities

Sand Layer centroid	5.635	m
Base plate plus two 1/8" porous plates	19	mm total thickness
Base plates centroid	5.9405	m

Sand layer

Depth to wt	295	mm
Depth below wt	297	mm
Equivalent depth (approximate)	29.6	m
Depth to middle of layer	296	mm
Check wt above middle of layer	OK	
Check overall depth is less than 600	ERROR	not necessary as depths are arbitrary to achieve σ_m'

Excess pore pressure	0%	20%	40%	60%	
Effective vertical stress, σ_v' at mid-depth	214.9	171.9	128.9	86.0	KPa
Effective vertical stress, σ_v' at base	348.6	278.8	209.1	139.4	KPa
or σ_v'	3.25	2.60	1.95	1.30	tsf
Ko	0.5	0.5	0.5	0.5	
σ_m' (mid-depth) target value see calc. earthq04.xls	**143.3**	114.6	86.0	57.3	KPa
σ_m' (base)	232.4	185.9	139.4	92.9	KPa
Go (round particles) at mid-depth	111.14	99.41	86.09	70.29	MPa
Go (angular particles) at mid-depth	**123.68**	110.62	95.80	78.22	MPa
Go (round particles) at base of layer	141.55	126.60	109.64	89.52	MPa
Go (angular particles) at base of layer	157.52	140.89	122.01	99.62	MPa

ESB design, calculation contd.

Data from Table 4.10 of shear modulus for sands, angular particles, ref 1

Equivalent uniform G calculated at mid-depth (assuming angular particles)

Strain amplitude	A	n	Strain %	0%	20%	40%	60% excess pp
10^{-6}	1	0	0.0001	**123.68**	110.62	95.80	78.22 MPa
10^{-5}	0.93	0.01	0.001	116.02	103.54	89.41	72.71 MPa
5×10^{-5}	0.83	0.03	0.005	105.35	93.60	80.36	64.82 MPa
10^{-4}	0.75	0.05	0.01	96.85	85.66	73.13	58.51 MPa
2.5×10^{-4}	0.56	0.1	0.025	75.50	66.04	55.57	43.57 MPa
5×10^{-4}	0.43	0.16	0.05	61.05	52.69	43.58	33.35 MPa
10^{-3}	0.3	0.22	0.1	44.86	38.20	31.05	23.19 MPa
2.5×10^{-3}	0.15	0.3	0.25	24.03	20.10	15.97	**11.55** MPa

Data from Table 4.12 for damping factor h for sands, ref 1

Strain amplitude	$h_{average}$	$h_{maximum}$	$h_{minimum}$	Strain amplitude (%)	Average damping (%)
10^{-6}	0.026	0.04	0.016	0.0001	2.6
10^{-5}	0.03	0.04	0.018	0.001	3.0
5×10^{-5}	0.033	0.042	0.02	0.005	3.3
10^{-4}	0.037	0.048	0.026	0.01	3.7
2.5×10^{-4}	0.055	0.068	0.04	0.025	5.5
5×10^{-4}	0.08	0.098	0.06	0.05	8.0
10^{-3}	0.12	0.145	0.092	0.1	12.0
2.5×10^{-3}	0.174	0.2	0.148	0.25	17.4

Ref 1: Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997, p64.

Average strain and box displacement

Width of ESB	315	mm
Length of ESB	800	mm
Area of soil	0.252	m^2
Area of rubber per layer	0.0675	m^2
Mass of soil in ESB	260	kg approximately
Mass of ESB container (above base plate)	117	kg
Weight of soil and ESB above mid depth	93	KN approximately, based on half soil and ESB mass

Average Strain

Earthquake amplitude		0%	5%	7%	9%	10%	
Average base shear stress		0	14.492713	20.289799	26.086884	28.98543	KN/m^2
Average shear modulus	10	0.00E+00	1.45E-03	2.03E-03	2.61E-03	2.90E-03	strain
(MPa)	12	0.00E+00	1.21E-03	1.69E-03	2.17E-03	**2.42E-03**	strain
	14	0.00E+00	1.04E-03	1.45E-03	1.86E-03	2.07E-03	strain
	16	0.00E+00	9.06E-04	1.27E-03	1.63E-03	1.81E-03	strain
	18	0.00E+00	8.05E-04	1.13E-03	1.45E-03	1.61E-03	strain
	20	0.00E+00	7.25E-04	1.01E-03	1.30E-03	1.45E-03	strain
	22	0.00E+00	6.59E-04	9.22E-04	1.19E-03	1.32E-03	strain
	24	0.00E+00	6.04E-04	8.45E-04	1.09E-03	1.21E-03	strain
	26	0.00E+00	5.57E-04	7.80E-04	1.00E-03	1.11E-03	strain
	28	0.00E+00	5.18E-04	7.25E-04	9.32E-04	1.04E-03	strain
	30	0.00E+00	4.83E-04	6.76E-04	8.70E-04	9.66E-04	strain
	32	0.00E+00	4.53E-04	6.34E-04	8.15E-04	9.06E-04	strain

ESB design, calculation contd.

Shear stiffness, MPa	G_{av}	G_{rubber}	0%	5%	7%	9%	10%
Average displacement	10	0.67	0	0.87	1.22	1.57	1.74 mm
at top of ESB container	12	0.80	0	0.72	1.01	1.30	**1.45** mm
	14	0.93	0	0.62	0.87	1.12	1.24 mm
	16	1.07	0	0.54	0.76	0.98	1.09 mm
	18	1.20	0	0.48	0.68	0.87	0.97 mm
	20	1.33	0	0.43	0.61	0.78	0.87 mm
	22	1.47	0	0.40	0.55	0.71	0.79 mm
	24	1.60	0	0.36	0.51	0.65	0.72 mm
	26	1.73	0	0.33	0.47	0.60	0.67 mm
	28	1.87	0	0.31	0.43	0.56	0.62 mm
	30	2.00	0	0.29	0.41	0.52	0.58 mm
	32	2.13	0	0.27	0.38	0.49	0.54 mm

Conclusion

One solutions is shown at 60% excess pore pressure, at a strain of 2.5×10^{-3} and 10% acceleration.
The average shear modulus of the ESB container would be 12 MPa (800 KPa for the rubber).
Deflection at the top of the ESB container would be around 1.5 mm.

ESB DESIGN
MODEL 4, SERIES 1

The attached worksheet present a series of calculations concerning the design of the ESB container models for Model 4 of Series 1 under the EQEN test series. An outline of the models is presented in the word document entitled Earthquake Model Test Plan.

The calculation aims simply to compute the shear modulus appropriate to a Nevada sand of specified void ratio under a given mean effective confining pressure. This low strain modulus is then degraded by a range of excess pore pressures, which are chosen as a percentage of the effective vertical stress. Strain degradation is based on the standard curves reproduced in the Handbook on liquefaction remediation of reclaimed land (PHRI).

The shear modulus is then obtained as a function of strain and excess pore pressure. This is compared with the strain calculated by assuming a uniform shear modulus for the entire container and computing the shear as a function of the lateral acceleration field (treated pseudo-statically). This is based on a crude assumption that at around mid-depth the mass of half the soil and half the container (above the base plate) are subject to a D'Alembert body force in a lateral direction. Clearly this is not precise, nor is it strictly at the correct elevation in the ESB container (mid depth in the loose layer is around 100 mm above the base of the container) but for the purposes of this calculation this is considered to give a solution of the right order of magnitude.

A combination of strain level and shear modulus is chosen as a compatible set, and the excess pore pressure and lateral acceleration field deduced. Finally the displacement of the chamber is calculated and the design rubber stiffness deduced.

ESB Design, Model 4 (Nevada sand)

This calculation is based on earthq04.xls and solves for the design stiffness of the ESB container for Models 1 and 2 of Series 1. A base plate and two porous plates are assumed.

Nevada sand (density and depth to achieve mean effective confining pressure)

Maximum void ratio	0.756	
Minimum void ratio	0.516	
Specific gravity	2.64	
Sand Relative density	35%	
Void ratio	0.673	fixed, as has influence on Go
Dry weight	15.5	KN/m^3
Bouyant weight	9.6	KN/m^3
Saturated weight	19.4	KN/m^3
Nevada sand D_{50} (approx)	0.18	mm
Nevada sand D_{10} (approx)	0.11	mm

Nominal g at 6 m 50 gravities

Sand Layer centroid	5.3575	m
Base plate plus two 1/8" porous plates	19	mm total thickness
Base plates centroid	5.9405	m

Sand layer

Depth to wt	370	mm
Depth below wt	777	mm
Equivalent depth (approximate)	57.4	m
Depth to middle of layer	573.5	mm
Check wt above middle of layer	OK	
Check overall depth is less than 600	ERROR	not necessary as depths are arbitrary to achieve σ_m'

Excess pore pressure	0%	20%	40%	60%	
Effective vertical stress, σ_v' at mid-depth	343.1	274.5	205.9	137.2	KPa
Effective vertical stress, σ_v' at base	589.3	471.4	353.6	235.7	KPa
or σ_v'	5.49	4.40	3.30	2.20	tsf
Ko	0.5	0.5	0.5	0.5	
σ_m' (mid-depth) target value see calc. earthq04.xls	**228.7**	183.0	137.2	91.5	KPa
σ_m' (base)	392.9	314.3	235.7	157.1	KPa
Go (round particles) at mid-depth	140.43	125.61	108.78	88.82	MPa
Go (angular particles) at mid-depth	**156.28**	139.78	121.05	98.84	MPa
Go (round particles) at base of layer	184.05	164.62	142.56	116.40	MPa
Go (angular particles) at base of layer	204.81	183.19	158.65	129.54	MPa

ESB design, calculation contd.

Data from Table 4.10 of shear modulus for sands, angular particles, ref 1

Equivalent uniform G calculated at mid-depth (assuming angular particles)

Strain amplitude	A	n	Strain %	0%	20%	40%	60% excess pp
10^{-6}	1	0	0.0001	**156.28**	139.78	121.05	98.84 MPa
10^{-5}	0.93	0.01	0.001	147.37	131.52	113.57	92.35 MPa
5×10^{-5}	0.83	0.03	0.005	135.22	120.14	103.15	83.20 MPa
10^{-4}	0.75	0.05	0.01	125.63	111.12	94.86	75.90 MPa
2.5×10^{-4}	0.56	0.1	0.025	100.54	87.94	74.00	58.02 MPa
5×10^{-4}	0.43	0.16	0.05	83.91	72.42	59.89	45.83 MPa
10^{-3}	0.3	0.22	0.1	63.62	54.18	44.04	**32.89** MPa
2.5×10^{-3}	0.15	0.3	0.25	35.55	29.74	23.62	17.08 MPa

Data from Table 4.12 for damping factor h for sands, ref 1

Strain amplitude	$h_{average}$	$h_{maximum}$	$h_{minimum}$	Strain amplitude (%)	Average damping (%)
10^{-6}	0.026	0.04	0.016	0.0001	2.6
10^{-5}	0.03	0.04	0.018	0.001	3.0
5×10^{-5}	0.033	0.042	0.02	0.005	3.3
10^{-4}	0.037	0.048	0.026	0.01	3.7
2.5×10^{-4}	0.055	0.068	0.04	0.025	5.5
5×10^{-4}	0.08	0.098	0.06	0.05	8.0
10^{-3}	0.12	0.145	0.092	0.1	12.0
2.5×10^{-3}	0.174	0.2	0.148	0.25	17.4

Ref 1: Handbook on Liquefaction remediation of reclaimed land, PHRI editor, Balkema 1997, p64.

Average strain and box displacement

Width of ESB	315 mm
Length of ESB	800 mm
Area of soil	0.252 m^2
Area of rubber per layer	0.0675 m^2
Mass of soil in ESB	270 kg approximately
Mass of ESB container (above base plate)	117 kg
Weight of soil and ESB above mid-depth	95 KN approximately

Average Strain

Earthquake amplitude		0%	5%	7%	9%	10%	
Average base shear stress		0	14.889267	20.844974	26.800681	29.77853	KN/m^2
Average shear modulus	10	0.00E+00	1.49E-03	2.08E-03	2.68E-03	2.98E-03	strain
(MPa)	12	0.00E+00	1.24E-03	1.74E-03	2.23E-03	2.48E-03	strain
	14	0.00E+00	1.06E-03	1.49E-03	1.91E-03	2.13E-03	strain
	16	0.00E+00	9.31E-04	1.30E-03	1.68E-03	1.86E-03	strain
	18	0.00E+00	8.27E-04	1.16E-03	1.49E-03	1.65E-03	strain
	20	0.00E+00	7.44E-04	1.04E-03	1.34E-03	1.49E-03	strain
	22	0.00E+00	6.77E-04	9.47E-04	1.22E-03	1.35E-03	strain
	24	0.00E+00	6.20E-04	8.69E-04	1.12E-03	1.24E-03	strain
	26	0.00E+00	5.73E-04	8.02E-04	1.03E-03	1.15E-03	strain
	28	0.00E+00	5.32E-04	7.44E-04	9.57E-04	**1.06E-03**	strain
	30	0.00E+00	4.96E-04	6.95E-04	8.93E-04	**9.93E-04**	strain
	32	0.00E+00	4.65E-04	6.51E-04	8.38E-04	9.31E-04	strain

ESB design, calculation contd.

Shear stiffness, MPa	G_{av}	G_{rubber}	0%	5%	7%	9%	10%
Average displacement	10	0.67	0	0.89	1.25	1.61	1.79 mm
at top of ESB container	12	0.80	0	0.74	1.04	1.34	1.49 mm
	14	0.93	0	0.64	0.89	1.15	1.28 mm
	16	1.07	0	0.56	0.78	1.01	1.12 mm
	18	1.20	0	0.50	0.69	0.89	0.99 mm
	20	1.33	0	0.45	0.63	0.80	0.89 mm
	22	1.47	0	0.41	0.57	0.73	0.81 mm
	24	1.60	0	0.37	0.52	0.67	0.74 mm
	26	1.73	0	0.34	0.48	0.62	0.69 mm
	28	1.87	0	0.32	0.45	0.57	**0.64** mm
	30	2.00	0	0.30	0.42	0.54	**0.60** mm
	32	2.13	0	0.28	0.39	0.50	0.56 mm

Conclusion

A solution exists at 60% excess pore pressure, with limiting strain of around 10^{-3} and 10% earthquake. The average shear modulus of the ESB container would be 28-30 MPa (around 2 MPa for the rubber). Deflection at the top of the ESB container under a 10% earthquake is of the order of 0.6 mm.